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Applications of Aerospace Technology to Petroleum Extraction and Reservoir Engineering

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Prepared for

National Aeronautics and Space Administration
Office of Energy Programs

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Applications of Aerospace Technology to Petroleum Extraction and Reservoir Engineering

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October 30, 1977

Prepared for

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PREFACE

The work described in this report was performed by the Earth and Space Sciences, Control and Energy Conversion, and Applied Mechanics Divisions of the Jet Propulsion Laboratory.

Individuals primarily responsible for the content of individual sections of this report are:

Section		Individuals
1.	Introduction	L. Jaffe
2.	Phase 1 Method and Procedure	L. Jaffe
3.	Assessment of Most Significant and Promising Problems	L. Jaffe
4.	Recommendations for Phase 2	L. Jaffe, P. Gordon, J. Marte, L. Back
5.	Supplementary Recommendations for Phase 2	L. Jaffe, P. Gordon, J. Marte, L. Back
6.	Phase 2 Procedure	L. Jaffe
7.	Determining Reservoir Inhomogeneities and Position of Induced Fractions, Fire and Flood Fronts	S. Parthasarathy, L. Jaffe
8.	Determining Oil Saturation, Permeability Porosity and other Reservoir Properties	E. Collins
9.	Perforating Deep Holes, and Deep into the Formation	E. Collins
10.	Downhole Pressure Measurements at High Temperatures	M. Berdahl
11.	Reducing Thermal Stress and Heat Losses in Casings of Steam Injection Wells	L. Back
12.	Water Supply for Injection	M. Humphrey
13.	Non-polluting Heat to Generate Injection Steam	J. Houseman, G. Hsu, W. Owen
14.	Seals and Flexible Components for Downhole Use	J. Ingham
15.	Long Life Downhole Drill Motor	P. Gordon

Section		Individuals
16.	Miscellaneous Problems	L. Jaffe, P. Gordon, J. Marte, L. Back
17.	Conclusions and Plans	L. Jaffe

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We would like to express our appreciation to the many individuals in industry, universities, and government, and at JPL, who contributed information, advice, and time. Their names are given in Appendix B. Without their cooperation and help, this study could not have been carried out.

This work was carried out under NASA contract NAS7-100.

ABSTRACT

The purpose of this study was to determine whether aerospace techniques can help solve significant problems in petroleum extraction and reservoir engineering. Through contacts with the petroleum industry, the petroleum service industry, universities and government agencies, important petroleum extraction problems were identified. For each problem, areas of aerospace technology that might aid in its solution were also identified, where possible. Some of the problems were selected for further consideration. Work on these problems led to the formulation of specific concepts as candidates for development. Each concept is addressed to the solution of specific extraction problems and makes use of specific areas of aerospace technology.

The following concepts were examined in this study and they appear feasible. Other concepts were noted but not examined in this work.

Problem	Concept
Determining reservoir inhomogeneties and position of induced fractures, fire location and flood fronts.	Hole-to-hole seismic tomography.
Determining or horizontal and vertical saturation, permeability, porosity, and other reservoir properties away from borehole.	Side-hole drilling
Perforating deep holes, and deep into formation.	Multiple side-hole drilling
Downhole pressure measurements at high temperatures.	Variable-capacitance gage, Resistance strain-gage of sputtered thin films.
Thermal stresses and heat losses in steam injection wells.	Prefabricated double-walled tubing with insulation between walls. Running cooling water down annulus between tubing and casing.
Upgrading water supply for steam injection or micellar flooding	Reverse osmosis plus distillation. Distillation utilizing a solvent, solar ponds, blending, or surfactants.
Non-polluting heat to generate injection steam.	2-stage combustion, scrubbing between stages. Desulfurizing crude with chlorine. Solar heat (not economic).
Seals and flexible components for downhole use.	Cross-linking or glass reinforcement to increase high-temperatures strength. Incorporating flexible units into rigid high-temperature polymers.

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EXECUTIVE SUMMARY

Very large amounts of petroleum exist in the United States in the form of known, located, resources which cannot be produced economically with conventional techniques. There is a growing interest in methods, such as enhanced recovery techniques and better reservoir engineering, that may permit economic recovery of this badly needed oil and gas.

There are a number of technical problems to be overcome in developing the methods needed. Considerable effort on them is under way, some of it paid for by the petroleum industry, some sponsored by the government.

More or less independently of the petroleum industry, a large amount of effort and technical skill has been devoted to the U.S. space program. This has led to the development of a number of areas of technical knowledge and skill related to aerospace. In recent years, Congress and the National Aeronautics and Space Administration (NASA) have increasingly emphasized the desirability of utilizing this technical knowledge and ability "back on Earth".

Some interchange of technology between aerospace and petroleum has already occurred. There has been considerable interest, for example, in the possibility of using remote sensing from earth satellites to help find oil and gas. Realizing that other possibilities might still be unrecognized, the NASA Office of Energy Programs initiated a study at Jet Propulsion Laboratory (JPL) in Pasadena, California, aimed at determining which additional problems in petroleum exploration, if any, could be aided by utilization of aerospace techniques. A report on that exploration study was issued earlier.

One conclusion arising from the exploration study was that it would be worthwhile to undertake a companion study aimed at identifying possible applications of aerospace technology to petroleum extraction and reservoir engineering. NASA asked JPL to conduct this study also.

JPL is part of the California Institute of Technology. Under contract with NASA, it has grown into a leading research and development center, and is the center for U.S. planetary missions. Though most of JPL's effort continues to be oriented toward space missions, it is not limited to this area, or to NASA sponsorship. JPL activities in energy-related areas are growing in importance. They include activities related to geothermal energy; remote sensing, including its use in petroleum, mineral, and geothermal exploration; coal extraction; improved automotive engines; improved burners for power stations; low cost solar cells; and a variety of other techniques for utilizing solar energy.

METHODS USED IN THE STUDY

The first step in this one-year study was identification of the significant problems in petroleum production. A number of management and technical individuals in petroleum companies, petroleum service

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companies, universities, and government agencies were contacted by the JPL study team and asked to identify significant problems. Based on these contacts, a list of problems was prepared and a preliminary attempt was made to match each problem with areas of aerospace technology that might aid in its solution.

Each problem was then evaluated as to its importance to the petroleum industry, its importance to the Department of Energy, the likelihood that aerospace technology would contribute significantly to solving the problem, and the time likely to be required before a solution could be demonstrated. On the basis of this evaluation, some of the problems were chosen for further consideration.

An attempt was made to identify one or more concepts, utilizing aerospace technology, that could aid in solving the problems chosen. Some of these concepts were examined by members of the JPL study team, to the extent permitted by the available funding. Available literature was studied, and discussions were held with knowledgeable people in industry, at universities, and at government agencies. In some instances, preliminary mathematical analysis, laboratory experiments, or conceptual design was carried out.

CONCEPTS EXAMINED

The following concepts were examined in this study. The depth of examination varied from concept to concept.

Hole-to-Hole Seismic Tomography to Determine Reservoir Heterogeneities

For proper reservoir engineering and operation, an adequate description of the entire reservoir is necessary. Methods are needed for determining overall reservoir characteristics including existence of fractures, faults, zones of high or low porosity or permeability, buried sandbars, stream beds, reefs, other rock inhomogeneities, as well as gas, oil and water quantities and interfaces. In enhanced recovery operations, methods are needed for determining the position of flood fronts, fire location and induced fractures.

Tracer and pressure tests and production history give only an overall picture of the reservoirs; they do not show the nature or position of inhomogeneities. Logs and cores give data only at the boreholes. Conventional seismic techniques have inadequate resolution, and do not provide data on porosity or, with some exceptions, on the nature of the fluid.

The proposed concept involves placing seismic sources in a borehole and transmitting signals to phones in another borehole. The timing and amplitude of the direct arrival for each source-phone combination are measured. Data are reduced by tomographic techniques. Tomography is a mathematical technique, used particularly in biomedical work, for reconstructing an object from a set of its projections. Its output would be a cross-sectional diagram or image of the section between two boreholes, showing the distribution of seismic velocity and of seismic attenuation. This diagram would then be interpreted in terms

of reservoir inhomogeneities.

This method should show reservoir inhomogeneities with much higher resolution than seismic measurements from the surface and should readily indicate porosity variations and the presence and content of gas.

The aerospace contribution would include experience of NASA laboratories in tomography and data-processing, as well as in design of explosive devices and possible alternative sources.

Side-Hole Drill for Determination of Reservoir Properties

Knowledge of reservoir properties is essential for proper reservoir assessment and reservoir engineering. Among the needs identified are: obtaining well cores that are more representative of the reservoir conditions; better measurements of residual oil saturation; measurements of porosity and oil saturation away from the boreholes; and more representative and less costly measurements of permeability, including vertical permeability.

Core properties are changed by drilling, by exposure to drilling fluids, and by the temperature and pressure changes associated with transferral to the surface. Well log measurements are also affected by the drilling and especially by the drilling mud. Vertical permeability is particularly difficult to determine accurately.

The proposed concept is based on use of a drilling package which is lowered into the borehole and then drills one or more small-diameter holes several yards out, at right angles to the main bore. This then permits measurement and sampling out beyond the zone affected by drilling the main hole and by the drilling mud.

The machine is conceived as a long tubular enclosure containing various pumps, motors, and feed mechanisms. It would be lowered into the borehole to the desired level, and fixed in the desired position with a packer located at each end of the enclosure to seal out borehole fluid. Reservoir fluid would be drawn in, filtered, and pumped to the drill head for cooling and chip flushing. The side hole would be drilled. If desired, a core could be cut and stored. At the completion of the drilling operation, an instrumentation package could be placed in the side hole and would be available for subsequent data acquisition. The side hole may itself be packed off, and fluid samples could be obtained from it. The sequence may be repeated for additional locations.

If several side holes are drilled, spaced either horizontally or vertically, a pressure difference could be applied between them; by measuring the flow between the side holes, the horizontal or vertical permeability could be determined. By sweeping between side holes with solvents or other fluids, both mobile and immobile oil content could be determined.

The aerospace contribution to the proposed device includes expertise in mechanical design, in design and testing for operation under severe conditions, and in systems engineering.

Multiple Side-Hole Drill for Deep Perforation

Obtaining reliable deep perforations is difficult in deep wells, because the high fluid pressure partly counteracts that due to the explosive charge and the bore diameter is generally small, limiting the size of the charge. If the well behaves poorly after perforation, it may be difficult to tell whether the cause is poor completion or a poor reservoir.

Perforations deep into the rock may be desired in tight formations as a step toward massive fracturing.

The concept proposed is to use a side-hole drill. The device would differ from the version described above in that multiple side-holes would be drilled simultaneously, the fluid already present in the bore would be used for drilling, and instrumentation and sampling provisions would be omitted, except for measurements to confirm the penetration depth of each side hole.

Capacitance or Resistance Gages for High-Temperature Downhole Pressure Measurements

Downhole pressure measurements with high accuracy, sensitivity, and stability are needed for reservoir engineering. Deep boreholes and those employed in thermal recovery are generally hot. The most accurate pressure measurement system available is limited to 300°F; it responds too slowly to be used in measurements of pressure vs. depth. Systems that can measure at higher temperatures record downhole and must be retrieved to obtain the data.

Two concepts are suggested. One uses a variable capacitance sensor. Downhole electronics are necessary with this sensor, and these limit the operating temperature to an estimated 525°F.

For higher temperature capability, an approach using resistance strain gages is suggested. The strain gages would be vacuum-sputtered thin film. No downhole electronics would be required.

With both designs, the pressure readings are insensitive to temperature, and may be made rapidly to measure pressure vs. depth. Readings are displayed and recorded at the surface.

The aerospace contribution includes experience in design, fabrication, and test of pressure and other sensors and of remotely-reading sensing systems for accurate measurements over extended periods of time, under severe environmental conditions. Other pertient experience includes data transmission, environmental testing, and systems engineering.

Sealed Insulation and Water Cooling to Reduce Thermal Stresses and Heat Losses in Steam Injection Wells

The depth at which steam injection is an economic recovery method is limited by heat losses through the walls and thermal stresses in the casing and cement; these become more serious as the pressure and there-

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fore the steam temperature increase.

The proposed concept is based on the use of prefabricated double-walled tubing, with high performance insulation installed and sealed between the walls by welding. The threaded ends of the inner tube are exposed. At the well, the tubing is run and pulled in the usual way, using standard couplings. The surrounding steel protects the insulation from well fluid and pressure, which would otherwise degrade its performance severely. A substantial cost reduction should result.

In addition, a small amount of cooling water can be run down the annulus between the injection tubing and the casing to pick up some of the heat that would otherwise be lost; at the formation level this water, now heated, mixes with the steam and is injected. This provides control of the annulus fluid without need for a downhole packer.

The aerospace contribution includes familiarity with heat flow associated with fluid flow, with design for severe environments, and with the high performance insulation methods and materials. It also includes familiarity with use of fluid cooling to reduce operating temperatures and at the same time recover heat that would otherwise be lost.

Reverse Osmosis Plus Distillation Concepts to Upgrade Water for Enhanced Recovery

Both steam injection and micellar-polymer flooding require water low in salt content. Available water may be scarce or brackish; produced water is usually high in salts.

A concept suitable for some conditions is reverse osmosis, probably through hollow fibers, combined with distillation. Distillation concepts include use of a solvent-enhanced azeotropic boiling mixture, solar ponds for concentration separation, and surfactants.

The aerospace contribution includes background in solar energy, thermal insulation, thin films, instrumentation, and new semipermeable membranes.

Reducing Emissions from Generation of Injection Steam, by Two-Stage Combustion or Desulfurization of Crude with Chlorine

Restrictions on air pollution, particularly SO_2 emissions, have a major impact on the use of steam injection in enhanced recovery. Field crude, the most available fuel, is usually high in sulfur. Stack gas scrubbing is expensive.

One concept is to burn the crude with limited air to produce heat and a gas in which sulfur occurs as H_2S. H_2S would be scrubbed from this gas, which would then be burnt with more air to produce more heat. Advantages as compared to conventional combustion and scrubbing are that a considerably lower volume of gas is handled in the scrubber, which should reduce the cost. Corrosion problems should be less severe, and since the combustion is at lower temperature, less NO_x pollutant is emitted,

Another concept is chlorination of the crude at room temperature and ambient pressure, followed by dechlorination with steam, and washing. It promises a method much simpler to carry out in an oil field than catalytic hydrodesulfurization, the process generally used in refineries.

Aerospace contributions include expertise in the chemical aspects of combustion originating from work on rocket propulsion and involving considerable experience in utility power plant combustion. Extensive work on polymers for use in solid propellants has generated considerable knowledge of sulfur binding in organic materials. Also, NASA has sponsored work on coal desulfurization by low temperature chlorinolysis for the past 4 years; this is now being supported by the Department of Energy.

New Formulations and New Polymers for Downhole Seals and Flexible Components

Many downhole devices - logging tools, cables, packings, downhole drill motors, etc. - utilize rubber and other elastomers in such components as seals, sleeves, electrical insulation, flexible elements, and so forth. At downhole temperatures these components often fail or have short life.

The concept is development of elastomers with improved high temperature properties by: (a) increasing the strength of polymers that are soft at high temperatures through cross-linking and through reinforcement with glass fibers; and (b) increasing the flexibility of polymers, such as poly(phenylquinoxaline), that are rigid at high temperatures through incorporation of flexible units into their molecular structure.

This effort is sponsored by the Department of Energy and utilizes extensive aerospace experience in the synthesis of polymers and development of elastomers for solid propellant rocket fuel.

Long-Life Downhole Drill Motor

With conventional rotary drilling, rotation of long lengths of drill pipe results in pipe wear, extreme metal fatigue leading to failure of the pipe, friction between the pipe and hole which reduces available power at the bottom of the hole, and difficulties in drilling deviated holes accurately. Thus, there has been much incentive to develop improved downhole drill motors. So far, none has proven economic in the U.S. for straight drilling. The primary problems have been abrasion of bearings and seals, obtaining satisfactory speed and torque, lack of surface indication of drilling parameters, and, for electrical motors, downhole power transmission.

In view of the number and competence of the companies working on downhole motors, it appears that future contribution by aerospace technology is most likely to come in such areas as development of better elastomers, as described in the proceding item, and in helping individual companies solve particular problems associated with their individual, often proprietary, designs.

Potential aerospace contribution includes expertise in mechanical

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and electrical engineering, vibration analysis, fluid mechanics, stress analysis, materials, control, and systems engineering.

CONCEPTS EXAMINED IN OTHER WORK

The following concepts, for which aerospace technology should be of help, were not examined in this study, but have been the subject of other work.

- Reduction in drilling costs by high pressure drilling, automated drill rigs, vibratory drilling, or combustion-fracture drilling.
- Long-stroke screw-activated pump for drilling mud in deep wells and for hydrofracturing.
- Acoustic back-scatter log for fracture detection.
- Determining stresses in rock by measuring deformation when cuts are made in borehole wall.

CONCEPTS IDENTIFIED BUT NOT EXAMINED

The following concepts, which also utilize aerospace technology, have been identified but not further examined:

- Error-correcting codes and public service communications satellite to aid transmission of drilling and logging data to a central computer.
- Reservoir modeling using NASTRAN finite element method or by inversion of production data.
- Dextrin-grafted polymers to increase stability and reduce cost of polymer solutions.
- Surfactants from wood-pulp lignin-cellulose to reduce cost and adsorption of surfactants.
- Detailed maps of sea bottom by digital sonar, image-processed, and displayed as photomosaics and topo maps.
- Unmanned submersibles with imaging and with manipulators for inspection and manipulation of sea bottom equipment. Also, 1-atmosphere room for this purpose.
- Determining sea-bottom characteristics with unmanned submersibles.
- Satellite imaging, radar, and radiometry for sea-ice prediction.
- Arctic offshore communication via Marisat or via a marine communication satellite providing better arctic coverage.

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PROBLEMS AMENABLE TO AEROSPACE TECHNOLOGY

Aerospace technology also appears applicable to the following significant petroleum problems, however, no attempt has been made to identify specific concepts for their solution.

- Transmission of downhole data to surface during drilling, logging, and production.
- Logging sensors for use during drilling.
- Distinguishing hydrocarbons from water by borehole measurement.
- Gas compression.

STATUS

In general, the concepts examined appear technically feasible. Some seem to offer very attractive cost savings. Some of them doubtless have been proposed earlier.

The concepts have been discussed with individuals in the petroleum and petroleum service industries, and some of their comments are reflected in this report, which concludes the study effort funded by the NASA Office of Energy Programs. Any further development of the concepts outlined will depend on the interest of government or private organizations in supporting further work.

The concepts have been developed only to the extent detailed in this report. Some of the concepts could now be taken up by the petroleum and service industries for further development. Others would need development and demonstration as indicated in the report before they could enter service.

NASA's ultimate goal in initiating this study was to attain routine use of aerospace technology in petroleum extraction; this study was pursued to that end. NASA and JPL will therefore actively encourage those interested in further development and utilization of the concepts which emerged from this study, and would be pleased to assist or participate in further work.

SECTION I

INTRODUCTION

To aid in meeting the energy needs of the United States, the National Aeronautics and Space Administration (NASA) Office of Energy Programs initiated a study at the Jet Propulsion Laboratory (JPL) to determine whether aerospace techniques can help solve significant problems in petroleum extraction and reservoir engineering. The ultimate goal of the effort is to increase the recovery of petroleum from natural reservoirs through applications of techniques developed or primarily used in aerospace. The study was started because of NASA's interest in applying technology developed in the space program to problems on earth, especially to energy problems. An earlier study was conducted on possible applications of aerospace technology to petroleum exploration (Reported in JPL Document 5040-32, Ref. 1-1). In the course of that study, several persons in the petroleum industry suggested that a similar study on enhanced recovery would be worthwhile, because of the large amount of petroleum that remains in known petroleum reservoirs within the U.S. after completion of primary and secondary recovery efforts.

A. OBJECTIVES AND SCOPE

The specific objectives of this study were:

(1) To identify and evaluate technological problems associated with petroleum extraction and reservoir engineering.

(2) To identify and evaluate potential applications of aerospace technology to solution of problems selected from those identified under Objective 1.

The study was to include primary, secondary, and tertiary recovery, reservoir engineering and assessment, reservoir development, and operations, and associated techniques, such as measurement, instrumentation, and data handling. Enhanced recovery problems are emphasized. Problems concerning oil shale might be noted but not addressed. The study was limited to technical and cost problems only. Matters of government policy, pricing, etc., were outside of its scope.

The study was limited to assessment of problems and of possible approaches to their solution. It did not incorporate the development work required to solve the problems. That would be decided upon and undertaken subsequently, on the basis of the results of this study.

B. OVERALL PLAN

The overall effort was divided into two phases:

Phase 1 was aimed at identification and assessment of current problems in petroleum extraction, and identification of areas of aerospace technology that

may be applicable to each. Included is a selection of a few of those problems for further work.

Phase 2 was devoted to a series of specific study efforts, addressing the problems chosen in Phase 1 for further attention. Emphasis was placed on identifying promising concepts based on aerospace technology and on examining these concepts. The amount of effort, and therefore, the degree of detail varied from problem to problem.

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SECTION 2

PHASE 1 METHOD AND PROCEDURE

The primary technique used for identifying petroleum production problems was direct contact of JPL team members with knowledgeable persons in industry, as well as in universities and government. Table 2-1 lists these organizations. Appendix B gives the names of the individuals with whom the discussions were held. Additional information was obtained from a DOE-sponsored workshop on research needed to support enhanced oil recovery (as reported in Reference 2-1).

Problems stated by various companies and other sources were similar in many cases. Several hundred problem statements were obtained; when duplications and overlap were eliminated, about 110 technical problems pertaining to petroleum extraction remained. Table 2-2 lists these problems; they are described briefly in Appendix C. Problems stated that fell outside the scope of this study are listed in Table 2-3.

Some of the pertinent problems were rather general; some have been addressed by industry for many years. Some may have been solved by one company but still remain as problems to its competitors. All were cited as problems by industry or other sources, not by JPL.

The JPL study team reviewed the pertinent problems and attempted to identify matching areas of aerospace technology. In this effort they were aided by representatives and technical experts from all of JPL's technical divisions, covering the spectrum of technical disciplines available at the Laboratory. Specific concepts for approaching some problems emerged from these interactions and were noted for future consideration, but no serious effort was made to originate concepts at this early stage of the work. The matching aerospace technology identified for each problem is noted in Appendix C. (If aerospace organizations have developed applicable technology in the course of solving non-aerospace, earth-based problems, this is noted as aerospace technology.)

Each problem was then rated by the study team using the following criteria:

(1) Is the problem important to the petroleum production industry?

(2) Is the problem important to DOE?

(3) Is aerospace technology likely to contribute significantly to solving the problem?

(4) How many years are likely to elapse before a solution to the problem is demonstrated, if work is started now?

Taking these ratings into account, as well as such factors as work known to be in progress at JPL and elsewhere, the study team made tentative recommendations of problems to be worked on in phase 2 of this study.

A technical review board was then convened which included qualified experts from industry, universities, and government, as well as senior JPL personnel. Appendix A gives the membership of this board. The board reviewed and commented on the list of problems, the ratings assigned them, and the tentative recommendations for phase 2 work, as well as on suggestions for continued industry and DOE inputs.

Comments from this review were utilized, together with information obtained earlier, to prepare revised problem ratings, an assessment of the most significant and promising problems, and revised recommendations for phase 2. The revised problem ratings are given in Table 2-2 and in Appendix C; the assessment and recommendations follow.

Table 2-1. Organizations Contacted

Petroleum Producers

- Amoco Production Co.
- Atlantic Richfield Co.
- Berry Holding Co.
- Chevron Oil Field Research Co.
- Cities Service Oil Co.
- Getty Oil Co.
- Great Basins Petroleum Co.
- Long Beach (City of)
- McCulloch Oil Corp.
- Mobile Research and Development
- Charles W. Oliphant
- Phillips Petroleum Co.
- Shell Oil Co.
- Texaco, Inc.
- Union Oil Co. of California

Service Companies

- Baroid Petroleum Services Division/NL Industries
- COFLEXID
- General Electric Co., Space Division
- Halliburton Services
- Maurer Engineering
- Rockwell International, Rocketdyne Division
- Schlumberger-Doll Research Center
- United Geophysical Corp.
- U.S. Steel Corp., Electrical Cable Division
- Wel-gaard, Inc.

University Organizations

- California Institute of Technology
- Gulf Universities Research Consortium
- Mississippi State University
- Stanford University
- University of Southern California

Governmental

- Department of Defense
  - Defense Materials Research Center
- Department of Energy
  - Division of Oil, Gas, and Shale Technology
  - Division of Geothermal Energy
  - Bartlesville Energy Research Center
  - Lawrence Livermore Laboratory
  - Los Alamos Scientific Laboratory
  - Morgantown Energy Research Center
  - San Francisco Operations Office
  - Sandia Laboratories
- Department of Inerior
  - Geological Survey
- Institute Francais du Petrole

Table 2-2. Problem List and Ratings

No.	Title	Importance to Industry	Importance to DOE	Likelihood of Space Contribution	Years Until Demonstration	
A1a	Reduction in Drilling Costs	H	H	M	5-10	
A1b	Long Life Downhole Drill Motor	H	H	HM	?	*
A1c	Longer Life Drill Bits	H	H	M	2-5	
A2a	Improved Drilling Fluids	M	M	L	-	
B1a	Perforation of Casings	MH	L	LM	5	*
B2a	Sand Control	M	L	L	3-5	
B3a	Flow Regime Recognition	L	L	L	-	
C1a	Thermal Stress in Casings	M	H	HM	5	*
C1b	High Temperature Rubber	H	MH	MH	2	
C2a	Quality Control	H	L	MH	2	
C2b	Deep Well Pump	H	L	ML	5	
C2c	Electric Lead-thru for Sea Bottom Use	L	L	LM	2	
C2d	Cheaper Well Piping	M	L	L	-	
C3a	Hydrogen Sulfide Corrosion	H	MH	ML	5-10	
C3b	Carbon Dioxide Corrosion	M	ML	ML	5-10	
C3c	Salt Water Corrosion	L	M	L	-	
C3d	Corrosion Inhibitors	M	L	M	?	
D1a	Production from Low Permeability Reservoirs	H	H	L	5	
D1b	Damaged Zone Around Well Bore	L	M	LM	5	
D1c	More Effective Explosive Fracturing	LM	M	L	-	
D1d	Massive Fracturing of Plastic Rocks	L	M	L	-	
D1e	Determining Position of Induced Fractures	MH	MH	M	2-3	*
D1f	Controlling Position of Induced Fractures	H	MH	L	-	
D1g	Predicting Position of Induced Fractures	MH	MH	L	-	
E1a	Well Core Sampling & Analysis	H	H	M	5-7	

H = high, M = medium, L = low

*Considered one of the problems most significant and most promising for application of aerospace technology.

Note: See Appendix C for further information on each problem.

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Table 2-2. Problem List and Ratings (Continuation 1)

No.	Title	Importance to Industry	Importance to DOE	Likelihood of Space Contribution	Years Until Demonstration	
E1b	Measuring Fracture Toughness of Rocks	M	M	H	3-5	
E2a	High Temperature Downhole Pressure Measurements	H	M	H	3-5	*
E2b	High Temperature Well Logging	MH	MH	H	1-2	*
E2c	Logging Sensors for use during Drilling	MH	MH	H	5	*
E2d	Downhole Permeability Measurements	H	H	M	5-7	*
E2e	Improved Logging Method for Fractures	M	H	MH	5	*
E2f	Distinguishing Hydrocarbons from Water by Borehole Measurements	H	MH	M	5	*
E2g	Measuring Stresses in Reservoir and Bounding Rocks	L	M	H	0?	*
E2h	Measuring Fire Location	M	M	MH	5-7	*
E2i	Monitoring of Flood Fronts	M	M	M	5-7	*
E2j	Metering Polymers	L	M	MH	3	
E2k	Measurement of Concentration of Corrosion Inhibitors Downhole	L	L	MH	3	
E2l	Monitoring Production during Chemical Flooding	L	L	ML	2-3	
E3a	Measurements from Bottom of Hole during Drilling	M	H	LM	5	*
E3b	Transmission of Logging Data to the Surface	M	M	H	2	*
E3c	Transmission of Downhole Data during Production	M	M	H	5	*
E3d	Transmission of Drilling and Logging Data to and from Central Computer	M	L	H	2-3	
E4a	Interpretation of Well-to-well Tracer Data	H	M	ML	3-5	
E4b	Interpretation of Pressure Pulse Data	H	M	M	2-3	
E4c	Improved Interpretaion of Electric Well Logs	H	L	ML	-	
E4d	Correcting Well Logs for Drilling Mud Properties	M	L	ML	-	
E5a	Automatic Control of Micellar Flooding Operation	L	ML	ML	2-3	

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Table 2-2. Problem List and Ratings (Continuation 2)

No.	Title	Importance to Industry	Importance to DOE	Likelihood of Space Contribution	Years Until Demonstration	
E5b	Measuring & Controlling Fluid Flow in Enhanced Recovery	L	L	M	2-3	
E5c	Control of Downhole Pumps & Valves	ML	L	H	3-5	
E5d	Maintaining Drill-Ship Position	L	L	L	-	
F1a	Determining Residual Oil Saturation	H	H	M	5-7	*
F1b	Measuring Porosity & Oil Saturation away from Boreholes	H	H	M	5-7	*
F1c	Determining Reservoir Characteristics	H	H	HM	5-7	*
F1d	Cheaper Tracer Technique for Well-to-Well Flow	L	MH	L	-	
F1e	Outlining Reservoirs	L	H	L	-	
F1f	Determining Vertical Permeability Characteristics	H	M	M	5-7	*
F1g	Determining Continuous Phase in Reservoir	L	M	L	5-10	
F2a	Improved Numerical Modeling of Reservoirs	LM	M	LM	2-3	
F2b	Model for In-Situ Combustion	M	M	ML	5	
F2c	Calculating Slug Size for Micellar Flooding	M	M	LM	5-10	
G1a	Control of Viscosity of Injected Liquids & Gases	H	ML	M	5	
G1b	Stability of Polymer Solutions	H	M	M	5	*
G1c	Polymer Adsorption on Reservoir Rock	M	M	M	5	
G1d	Cost of Polymers	H	H	ML	?	*
G1e	Measurement of Polymer Concentration in Reservoir Fluid	ML	M	MH	1-2	
G1f	Preflush Conformance	MH	M	ML	5-10	
G1g	Handling High Pour-Point Oil	L	M	LM	-	
G2a	Stability of Surfactant Solutions	MH	HM	L	-	
G2b	Adsorption of Surfactants	MH	M	L	-	
G2c	Cost-effective Surfactants	MH	M	L	-	
G3a	Control of Effective Density of Injected Gases	H	M	M	5-10	
G4a	Permeability Inhomogeneity	H	M	ML	5-10	
G4b	Control of Gravitation Segregation by Permeability Modification	H	MH	ML	5-10	

Table 2-2. Problem List and Ratings (Continuation 3)

No.	Title	Importance to Industry	Importance to DOE	Likelihood of Space Contribution	Years Until Demonstration	
G4c	Chemical Plugging during Thermal Recovery	L	M	L	-	
G5a	De-emulsification of Produced Fluids	LM	M	L	2	
G6a	Treating Produced Water	L	M	M	2	
G6b	Water Supply for Steam Injection	M	H	M	2-3	*
G6c	Re-use of Produced Water	M	H	M	2-3	*
H1a	Carbon Dioxide Production	MH	H	L	-	
H1b	Separation of CO_2 from Produced Gases	LM	M	L	-	
H2a	Gas Compression	M	MH	LM	-	*
H3a	Heat Losses in Steam Injection	M	H	H	2-3	
H3b	Downhole Generation of Heat for Enhanced Recovery	M	H	L	-	
H3c	Steam Generation from Low-Quality Water	M	MH	ML	5	
H3d	Low Cost Steam	H	M	L	-	
I1a	Detailed Mapping of Sea Bottom	L	H	H	3	
I1b	Sea-bottom Characteristics	M	H	HM	2	*
I1c	Sea-Ice Prediction	L	M	H	0	
I1d	Offshore Weather Prediction	H	L	H	3-5	
I1e	Earthquake Prediction	M	H	H	?	*
I2a	Off-shore Platform Design	M	M	M	20	
I2b	Marine Drilling in Storms	M	M	L	-	
I2c	Iceberg Control	L	M	L	-	
I2d	Inspection & Manipulation of Sea Bottom Equipment	M	H	HM	3-5	*
I2e	Sea-Ice Hazard to Completed Wells	M	M	L	-	
I2f	Bringing Oil to Surface & Shore in Arctic Seas	H	M	L	-	
I2g	Permafrost	L	M	MH	0	
I2h	Coping with low Arctic Temperatures	M	L	MH	?	
I2j	Scheduling Arctic Logistics	L	M	M	?	
I2k	Deep Water Production	LM	M	M	5-10	

Table 2-2. Problem List and Ratings (Continuation 4)

No.	Title	Importance to Industry	Importance to DOE	Likelihood of Space Contribution	Years Until Demonstration	
I2l	Arctic Offshore Communication	L	L	H	0	*
Jla	Flue Gas Emissions	H	H	M	5	*
Jlb	Oil Desulfurization	H	M	M	5	*
J2a	Systems Approach to Regional Energy Needs	LM	M	M	5-10	
J2b	Technical Information for Government Actions	MH	M	L	-	
J2c	Obstacles to Unitization	H	M	L	-	
Kla	Flooding Methods for Enhanced Gas Recovery	M	M	L	-	
Klb	New Methods for Enhanced Recovery of Oil	H	H	L	-	
Klc	In-Situ Refining	M	L	L	-	

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Table 2-3. Problems Considered Outside the Study Scope

L. Problems of governmental policy and administration

L1a.	Price controls on petroleum
L1b.	Delays in allowing offshore development
L1c.	Excessive constraints on environmental quality
I1d.	Income tax provisions

M. Exploration problems

M1a.	Seismic prospecting for gas shale reservoirs
M1b.	Remote sensing of lineaments
M1c.	Remote sensing for oil
M1d.	Geochemical sensing of gas shale reservoirs
M1e.	Arctic offshore navigation

N. Utilization problems

N1a.	Gas from geopressured reservoirs
N1b.	Utilization of low BTU natural gas
N1c.	Utilization of low productivity gas wells

O. Research problems

O1a.	Rock deformation and fracture mechanics
O1b.	Phase equilibrium in CO_2 - H_2O - crude oil system

P. Problems not pertaining to petroleum

P1a.	Thermal techniques for extraction of oil from tar sands and oil shales
P1b.	Recovery of natural gas from coal seams

SECTION 3

ASSESSMENT OF MOST SIGNIFICANT AND PROMISING PROBLEMS

From the total list of about 110 problems shown in Table 2-2 and described in Appendix C, a subset of about 30 were selected as problems that are both highly significant in petroleum extraction and promising for application of aerospace technology. Each of these 30 is identified by an asterisk at the right of its entry in Table 2-2.

Thirty problems were too many for examination of the kind desired for Phase 2, with the resources available. A further selection from among these 30 is indicated in the recommendations that follow.

SECTION 4

RECOMMENDATIONS FOR PHASE 2

Effort recommended for phase 2 is listed below. If resources to support all of this effort are not available, preference was generally to be given to topics high on the list, except where a preliminary look indicated further effort is not worthwhile.

(1) Determining residual oil saturation, permeability, porosity, and other reservoir properties (Problems E1a, E2d, F1a, F1b, F1f). A concept to be considered is drilling 2 or more side holes perhaps 10 feet out into the reservoir from the well-bore. This would permit getting outside the zone affected by the mud and other effects of drilling the main hole. Various reservoir properties could then be determined, depending on the type of measurement made. Electrical log measurements could then be made between the side holes. One side hole could be pressurized and the flow into another side hole measured to determine the permeability; this flow could also be collected for analysis. Engineering design of the side hole drill would need primary attention.

(2) Determining reservoir characteristics, especially inhomogeneities (Problem F1c). One possible concept is acoustic tomography, as outlined in Reference 1-1. Other concepts should be sought.

(3) High temperature downhole measurements of pressure and other quantities (Problems E2a, E2b). A preliminary effort should be made to determine what work is underway on this problem, under ERDA and other sponsorship. If there seem to be significant gaps, concepts for their solution should be sought.

(4) Long life downhole drill motor (Problem A1b). A preliminary effort should be made to determine what work is underway on this problem under ERDA, aerospace, or other sponsorship, and what is known of Soviet equipment. Deficiencies in existing and proposed equipment should be identified. Concepts should then be sought for overcoming these deficiencies.

(5) Thermal stresses in casings of steam injection wells (Problem C1a). The heat transfer conditions should be examined and methods considered for decreasing heat transfer to the casing. Concepts include insulating between the tubing and the casing and perhaps also circulating fluid in this annulus. Flexible cements might also be considered. Only a small effort may be devoted to this topic.

(6) Perforation of casings (Problem B1a). If the side hole drill concept (Recommendation 1) appears feasible, consideration should be given to using an array of such drills for perforation, or torches followed by drills. Some thought may be given to additional perforation concepts.

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(7) Determining position of induced and natural fractures (Problems D1e, E2e). This should be considered as part of the effort on determining reservoir characteristics (Recommendation 2). For natural fractures, the acoustic backscatter log (see Reference 1-1) is an alternative concept and effort on it may be proposed separately.

(8) Data transmission up the hole (Problems E3a, E3b, E3c). This may be addressed as part of the effort on Recommendation 3.

(9) Concepts that may be at hand on the following problems should be recorded, but no significant study effort should be devoted to them:

(a) Flue gas emissions (Problem J1a)

(b) Oil desulfurization (Problem J1b)

(c) Water treatment (Problems G6a, G6b, G6c)

SECTION 5

SUPPLEMENTARY RECOMMENDATIONS FOR PHASE 2

Two other topics that warrant special attention are:

(1) Stability and cost of polymer solutions (Problems G1b and G1d). A significant effort would be necessary to determine what work has already gone on in this area and to develop promising new concepts. This problem would be worth studying if separate resources are available.

(2) Inspection and maintenance of sea-bottom equipment and determination of sea-bottom characteristics (Problems I1a, I1b, I2d). Work on this topic is being done by aerospace companies. Some effort is underway at JPL on closely related problems, utilizing unmanned undersea vehicles; perhaps some of this effort should be addressed specifically to this topic.

The following additional problems, identified in Section III as significant in petroleum extraction and promising for application of aerospace technology, should also be given particular consideration if resources become available:

(1) E2c. Logging sensors for use during drilling.

(2) E2f. Distinguishing hydrocarbons from water by borehole measurements.

(3) E2g. Measuring stresses in reservoir and bounding rocks.

(4) E2h. Measuring fire location.

(5) E2i. Monitoring of flood fronts.

(6) H2a. Gas compression.

(7) I2l. Arctic offshore communication.

SECTION 6

PHASE 2 PROCEDURE

The study efforts of Phase 2 were carried out by individuals or small groups, each working on a problem or concept. After review by study management, the results were presented to a technical review board (see Appendix A). On the basis of comments from the review board, additional work was done on some of the problems. Comments by the board were taken into account in preparing this report.

Primary attention in Phase 2 was devoted to two problems, and was based on the following concepts:

> Determining reservoir characteristics, especially inhomogeneities. (Problem 2 of Section 4; F 1c of Appendix C.) Concept: Hole-to-hole seismic tomography.
>
> Determining reservoir properties, including vertical permeability, away from the borehole. (Problem 1 of Section 4; E 1a, E 2d, F 1a, F 1b, F 1f of Appendix C.) Concept: Side-hole drilling.

Secondary effort was devoted to:

> High temperature downhole pressure measurements. (Problem 3 of Section 4; E 2a of Appendix C.) Concept: High temperature resistance strain gage.
>
> Thermal stresses and heat losses in casing of steam injection wells. (Problem 5 of Section 4; C 1a and H 3a of Appendix C.) Concepts: Run cooling water through annulus. Double-walled tubing with insulation between walls.
>
> Long life downhole drill motor. (Problem 4 of Section 4; A 1b of Appendix C.) No new concept was identified in this study. One approach was noted in a previous study (Ref. 1-1). Also, work on high temperature seals and flexible components is noted below.

A tertiary level of effort concerned:

> Water treatment (to permit, for example, use of produced or brackish water for steam injection or micellar flooding). (Problem 9c of Section 4; G 6a, G 6b, G 6c of Appendix C.) Concept: Desalination by reverse osmosis, combined with distillation.
>
> Non-polluting heat to generate injection steam. (Problems 9a and 9b of Section 4; J 1a and J 1b of Appendix C.) Concepts: Two-stage combustion, scrubbing between stages. Chlorine desulfurization of crude. Solar heat.

Several other problems were addressed to some extent in the examination of the primary concepts:

Determining position of induced and natural fractures. (Problem 7 of Section 4; D 1e and E 2e of Appendix C.) Determining position of induced fractures is included in the concept of hole-to-hole acoustic tomography (item A, above). Determining position of natural fractures was not specifically considered in this study. It was, however, considered in the previous study on application of aerospace technology to petroleum exploration (Ref. 1-1); the concept suggested was an acoustic backscatter log.

Perforation of casings. (Problem 6 of Section 4; B 1a of Appendix C.) The concept of side-hole drilling (item B, above) seemed applicable.

More effective explosive fracturing. (Problem D 1c of Appendix C.) The concept of side-hole drilling to place explosives seemed applicable.

Measuring fire location. (Problem E 2h of Appendix C. Mentioned in Section 5.) The concept of hole-to-hole acoustic tomography (item B, above) may be applicable.

Monitoring of flood fronts. (Problem E 2i of Appendix C. Mentioned in Section 5.) The concept of hole-to-hole acoustic tomography may be applicable.

Finally, a separately sponsored effort is also reported briefly here:

Seals and flexible components for high temperature downhole use. (Problem C 1b of Appendix C.) Concept: High temperature and reinforced elastometers.

Work on each of these problems and concepts is reported in the following sections of this report.

Concepts based on aerospace technology, and considered promising, had been identified in Phase 1 for a number of other problems. These were not addressed in Phase 2, either because the resources for the work would not stretch that far or because the problem was covered in the earlier exploration study (Ref. 1-1). These concepts and problems are listed in Section 16.

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SECTION 7

DETERMINING RESERVOIR INHOMOGENEITIES AND POSITION OF INDUCED FRACTURES, FIRE AND FLOOD FRONTS

Concept: Seismic sources in a borehole transmit signals to phones in another borehole. Timing and amplitude of the direct arrival for each source-phone combination are measured. A key factor is that data are reduced iteratively by techniques of tomography and refraction seismography to give diagrams or images of velocity and attenuation distribution over the cross-section. These are interpreted in terms of reservoir inhomogeneities.

A. PROBLEMS ADDRESSED

Both industry and DOE sources considered better methods of determining reservoir characteristics to be of high priority. Methods are needed for determining overall reservoir characteristics including existence of fractures, faults, zones of high or low porosity or permeability, buried sandbars, stream beds, reefs, other rock inhomogeneities, gas, oil and water quantities and interfaces.

For proper evaluation of a reservoir for primary production or enhanced recovery operations, an adequate description of the entire reservoir is necessary. Information on characteristics between the wells, not just at the wells, is important.

This problem was rated as one of the most significant and promising for application of aerospace technology. In the same category were also placed several related problems:

(1) Determining position of induced fractures.

(2) Measuring fire location.

(3) Monitoring of flood fronts.

These are all significant for proper control of enhanced recovery operations.

Techniques that are ordinarily used for determination of reservoir heterogeneities, fractures, and front locations include tracer flow tests, pressure transient tests, production history, and well logging and coring. Tracer and pressure tests and production history give only an overall picture of the reservoir; they do not show the existence or position of inhomogeneities. Logs and cores give data only at the boreholes.

In principle, some inhomogeneities should be detectable by conventional seismic reflection techniques. These techniques have, however, important limitations. Their resolution is usually inadequate for the needs of reservoir engineering. They give poor results with steeply dipping beds. They are impeded by overlying layers which are strong attenuators or strong reflectors. They give data on the acoustic velocity of the beds but not on their porosity and, with some exceptions, not on their fluid content. For all these reasons, seismic reflection methods have significant limitations even for exploration, and they are rarely used in production engineering.

In view of the needs, then, a different technique for determining reservoir inhomogeneities is suggested.

B. TECHNICAL METHOD

The proposed method, briefly stated, is as follows: seismic signals are transmitted from sources in a borehole to phones in another borehole (Figure 7-1). The timing and amplitude of the direct arrival for each source-phone combination are measured. Data are reduced by techniques of tomography (explained below), iterated with refraction seismography. The output is a cross-sectional diagram or image of the section between the two boreholes, showing the distribution of seismic velocity and of seismic attenuation (Figure 7-3). This diagram is then interpreted in terms of reservoir inhomogeneities, such as lithologic or porosity variations, faults, fractures, gas content, fire or flood fronts, etc.

The seismic signals may also be transmitted from sources at the surface to phones in a borehole, or vice versa; thus, the method may be used, with some degradation in performance, when only 1 borehole is available (See Figure 7-1).

What is tomography?

Tomography is the reconstruction of an object from a set of its projections. For an example refer to Figure 7-2. The test section here contains a small dense object. Projections are made in several directions parallel to the test section, by some technique such as acoustic, X-ray, etc. (Figure 7-2a). Each projection is a one-dimensional representation of the integrated density along the direction of projection. By suitably combining the data in several projections, the density distribution of the original section can be reconstructed (Figure 7-2b).

C. BACKGROUND OF METHOD

1. Hole-to-Hole Seismic Transmission

Though it is not unusual to place seismic recievers in boreholes to obtain data from seismic sources at the surface near the hole, such well-shooting has usually been done to obtain

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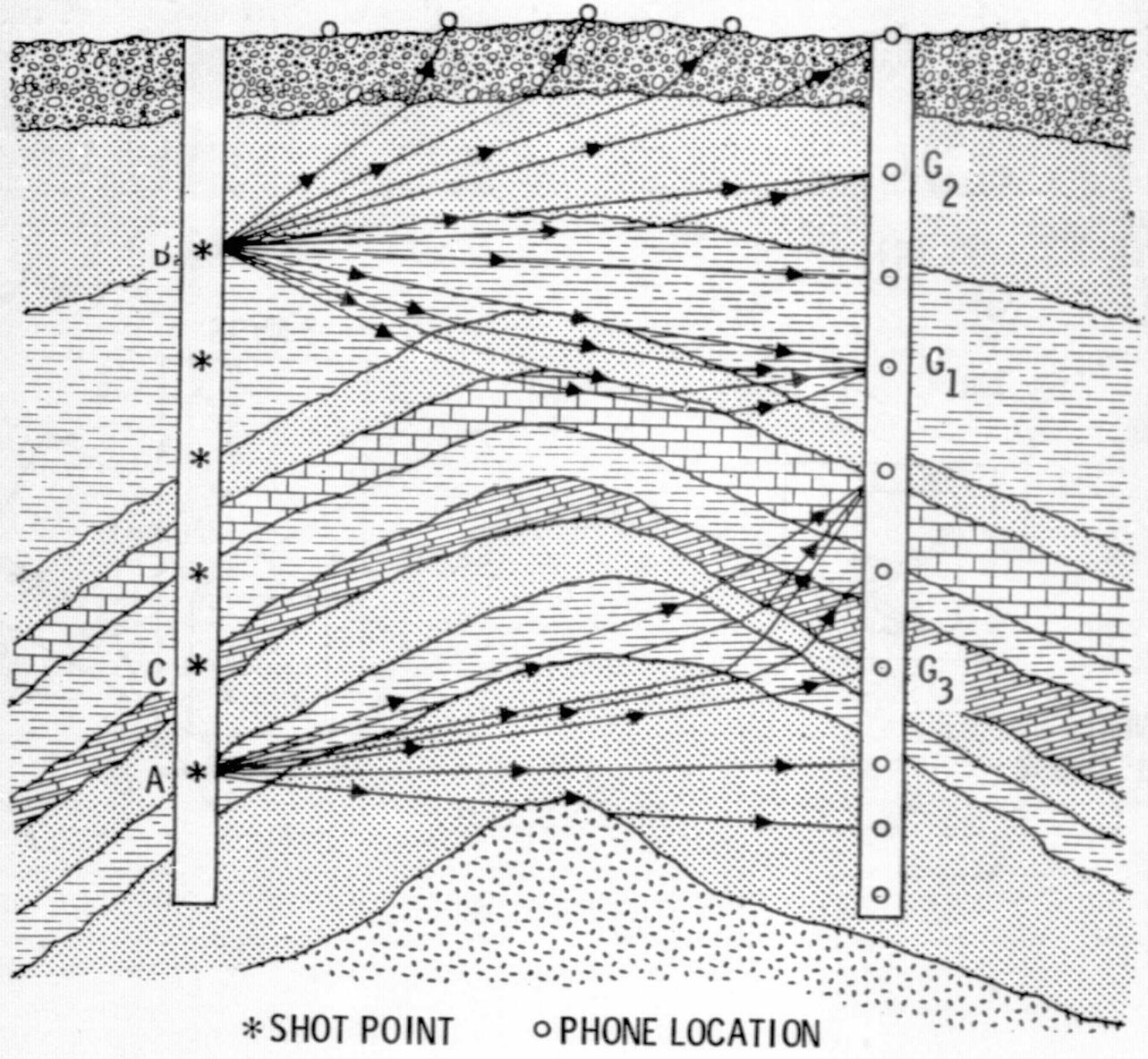

Figure 7-1. Source and Phone Positions and Acoustic Ray Paths for Seismic Tomography. (Conceptual)

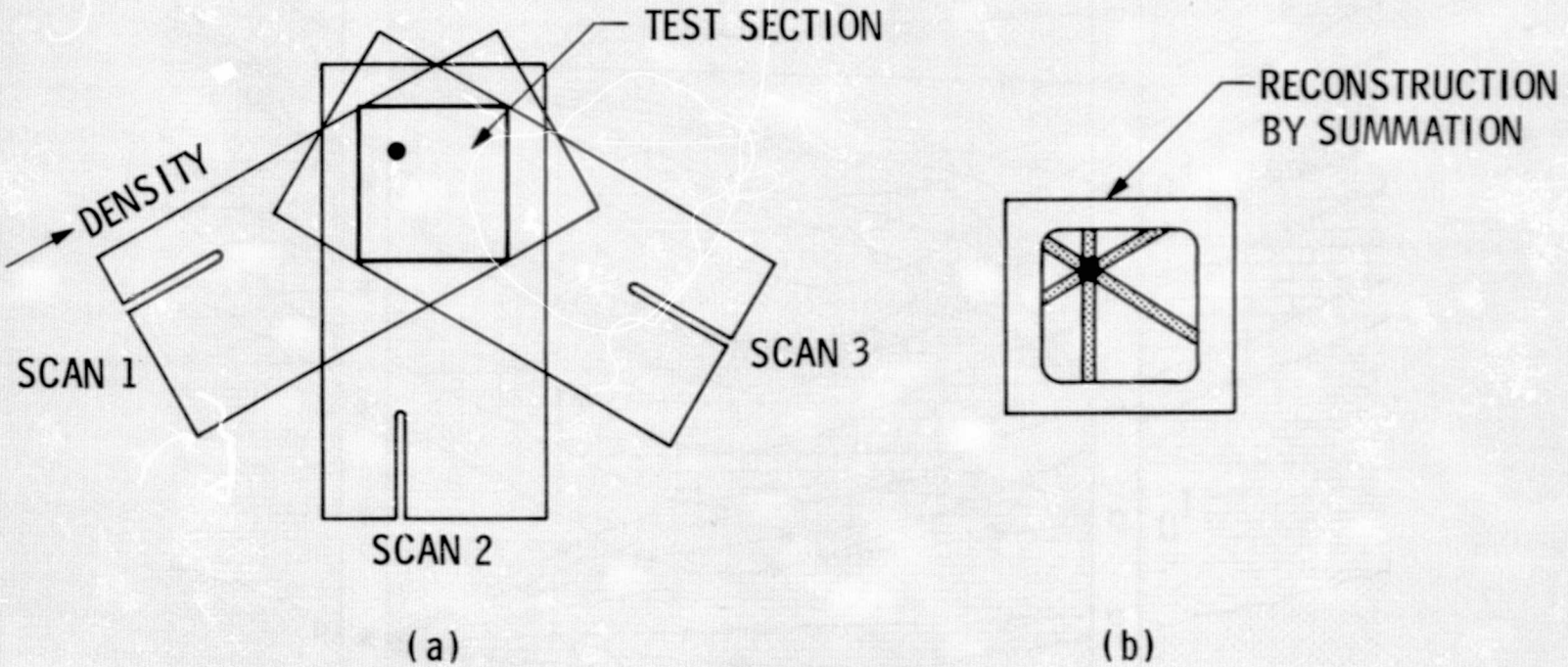

Figure 7-2. Elementary Example of Tomography (a) Multiple Projections of Test Section (b) Reconstruction

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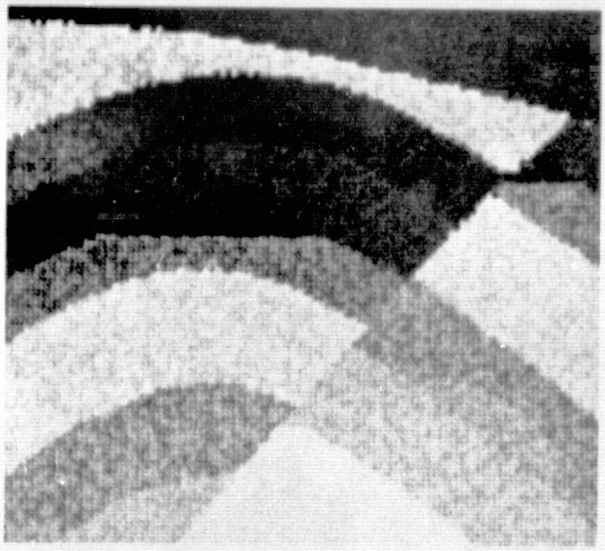
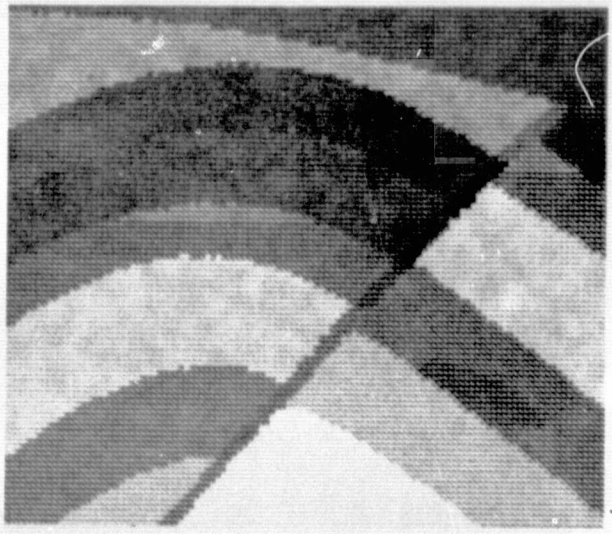


(a)



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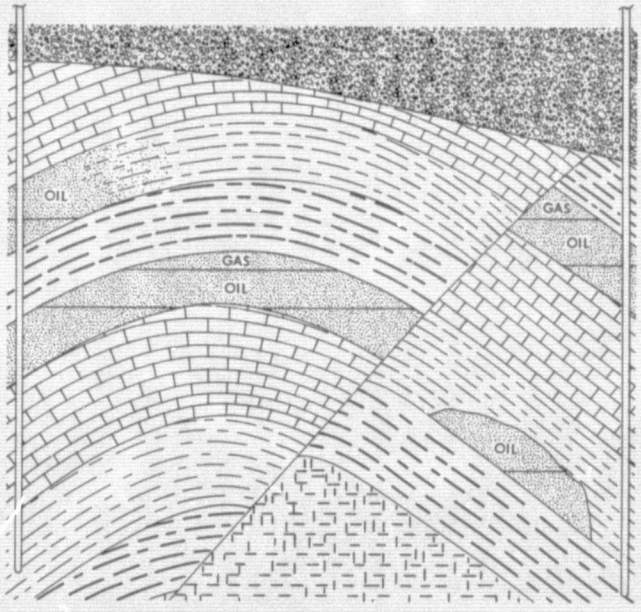

(c)

Figure 7-3. Output of Hole-to-Hole Seismic Tomography (Conceptual)
(a) Velocity Distribution Over Cross-Section
(b) Attenuation Distribution Over Cross-Section
(c) Interpretation

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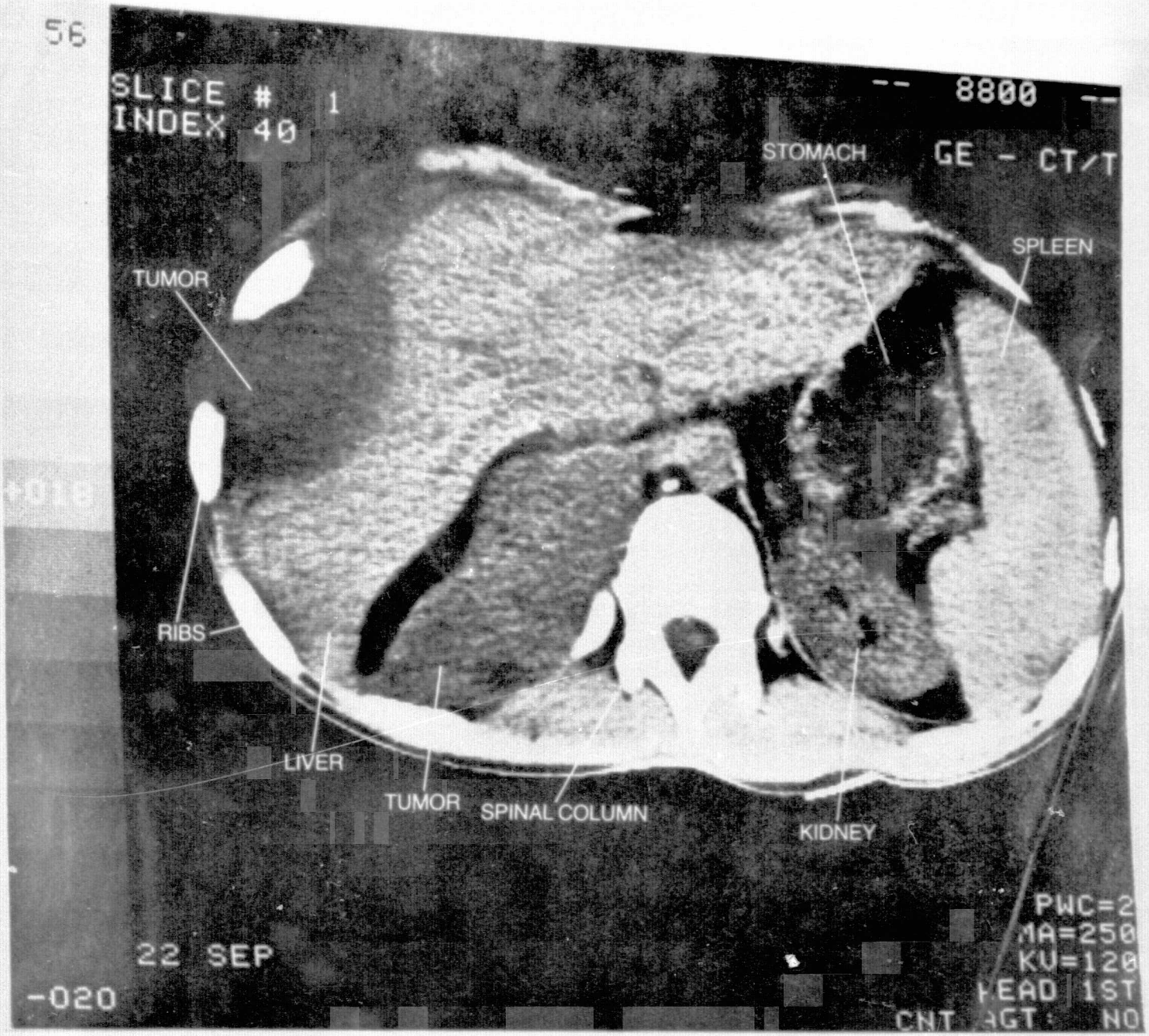

Figure 7-4. Tomograph of Human Body. Tomography by X-rays. Attenuation distribution is displayed (Ref. 7-8).

seismic velocity data for use in surface surveys or, sometimes, for lithologic information. As presently practiced, that approach does not develop information on stratigraphy or structure some distance away from the hole. Hole-to-hole seismic methods have occasionally been proposed to obtain velocity data which could be used in surface reflection surveys and also could give some indication of the stratigraphy and structure between the boreholes (Refs. 7-1 to 7-3). They have been used to locate the relative position of nearby boreholes (Ref. 7-4) and in attempts to locate an induced fracture at a borehole (see Ref. 7-4) and a fire front during in situ coal gasification (Ref. 7-5). Well-shooting has diminished in importance as acoustic velocity logs have come into use; hole-to-hole seismic techniques have never come into general use.

A major advantage of hole-to-hole seismic methods over reflection seismic measurements from the surface is that greater spacial resolution can be attained. The reason is that shorter wavelengths can be used, and the size of the features that can be resolved is directly proportional to the wavelength. Reflection methods from the surface are limited to long wavelengths, or equivalently low frequencies (below 100 or 150 Hz), by high acoustic losses arising from three characteristics:

(1) The long 2-way path through the earth from surface source to reflecting horizon and back to surface phone. The losses due to absorption, scattering, and spherical spreading all increase with the path length.

(2) The low acoustic reflectivity of horizons: typically about 10%.

(3) In some localities, the presence of highly absorbing or highly reflecting layers near the surface, which keep most of the signal energy from reaching the desired depth.

Moreover, the reflection technique works poorly when the dip is high, because horizons at high dip reflect downcoming waves off horizontally or even downward, rather than back to the surface.

Hole-to-hole transmission avoids these difficulties. The hole-to-hole distances in a field developed or under development are typically less than 1500 ft (500 m) and transmission is 1-way. In contrast, working from the surface, the depth may be 5000-20,000 ft (1500-6000 m) or more and since reflection requires a 2-way path, the path length is twice as great: 10,000-40,000 ft (3000-12000 m) or more. Because the hole-to-hole method uses transmission, the loss at an interface is only about 10%, vs. about 90% for reflection. Hole-to-hole paths avoid highly absorbing or reflecting near-surface layers. High dips do not interfere with hole-to-hole transmission.

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Since losses are much reduced with hole-to-hole techniques, higher frequencies can be utilized and resolution improved correspondingly. Additionally, the static corrections needed in surface reflection seismography to correct for surface layer properties are sometimes difficult to evaluate; a hole-to-hole technique does not need such corrections. Thus, hole-to-hole methods appear worth considering when boreholes are available.

2. Tomography

Tomography is at present commonly used in the field of medicine for observation of the soft tissues in the human body. In that application, an excitation source which may be ultrasound or X-ray, and suitable receivers outside of the human body, are moved to a number of positions in a plane intercepting the body. The resulting data can be geometrically manipulated (either mechanically or by computer) to produce a map of the acoustic or other properties (depending on the nature of the excitation) over the cross section. The technique has been successfully used to recover such complex features as the human face (Ref. 7-6) and is being increasingly used in medical diagnosis using X-ray projections for scanning the human brain. An example is shown in Figure 7-4.

The mathematical procedures for recovering the cross-section are well developed. A number of efficient algorithms are known, and computer programs for medical applications have been widely used for some years. JPL, in the course of its efforts on biomedical applications of space technology, has done significant work on tomography, and tomographic computer programs are available at JPL.

Work has recently been reported and is continuing on geologic application of tomography using electromagnetic signals (Ref. 7-7). The range in the earth of electromagnetic signals with short wavelengths (good resolution) is however quite small and the applicability of the electromagnetic technique to petroleum problems therefore seems limited. Bois et al (see Refs. 7-2 and 7-3) have carried out seismic experiments using for data reduction a method equivalent to a tomographic algorithm, though they did not explicitly recognize the equivalence.

In evaluating possible applications of space technology to petroleum exploration, hole-to-hole seismic tomography was suggested by some of the present authors and their colleqgues and considered in a preliminary fashion (Ref. 1-1). The method seems even more applicable to production problems than to exploration, since boreholes will necessarily be available for production. Tomography also gives promise of providing additional

information concerning reservoir characteristics because it can provide an absorption picture as well as a velocity picture; the two pictures together may permit evaluating such characteristics as porosity distribution and gas/liquid interfaces or fronts. Accordingly, the tomographic technique has been examined further in this study.

D. TECHNICAL ASPECTS

Various aspects of the proposed technique are considered in Appendix D. Important points developed in that Appendix may be summarized as follows:

(1) A wide variety of procedures and computer programs for tomographic inversion exist and are in use for other applications.

(2) A suitable downhole signal source would be a few grams or tens of grams of explosive. This should not damage a cased or uncased hole.

(3) With this source, the seismic energy loss at the wall of the borehole should be small.

(4) Signal from such a source should generally be detectable with adequate signal/noise ratio in another borehole at a distance of 300 m or more at a frequency of 1000-1500 Hz and at a distance of 1 km at 300-400 Hz.

(5) Correspondingly, the spatial resolution theoretically attainable is about 1 to 2 m with a 300 m borehole-to-borehole distance and 4-8 m with a 1 km distance.

(6) For tomography, the ray path from source to receiver must be known. Seismic ray paths are not straight lines; because of refraction, the paths depend upon the seismic velocities of the materials encountered. The suggested procedure is an iterative one: Straight-line paths are assumed for the first iteration. The tomographic reconstruction gives a first-cut velocity distribution over the section. This is used to calculate more accurate ray paths, by a ray-tracing program based on principles of refraction seismography. These ray paths are the basis of a second tomographic iteration, which gives a better velocity distribution. Ray tracing and tomography are repeated until the solution converges.

(7) Besides the most direct ray path from source to phone, alternative paths will generally exist because of refraction (focussing), reflection, diffraction, mode conversion, etc. In the data processing, directional stacking can provide considerable discrimination against most alternative paths. Consideration of signal strength and timing should permit

picking the direct arrival from among the multiples that are not removed by directional stacking.

(8) Low-velocity beds bounded by higher velocity beds, which cannot be seen in conventional refraction seismography, should not cause similar difficulties in hole-to-hole tomography. They should be revealed by their effect upon rays transmitted across them.

(9) Thick low-velocity beds may act as waveguides but signals transmitted in this way along an indirect path should be attenuated by directional stacking.

(10) Waves transmitted along the boreholes should be attenuated strongly by directional stacking, and can be further distinguished by their waveform.

(11) In prinicple, a borehole wave, from a surface source, and radiating energy into the rock as it travels downhole, might be used as a source instead of a series of downhole sources. Preliminary calculation indicates however that this will seriously degrade the resolution.

(12) Geophones clamped to the wall of the borehole are probably preferable to hydrophones. Three-axis geophones offer significant advantages over single-axis phones. Phones should be wired individually or in very short groups.

(13) Multiconductor downhole cables will be needed, or downhole telemetry equipment.

E. PROCEDURE

A procedure for hole-to-hole seismic tomography may be sketched as follows:

A borehole is selected for placement of the seismic sources and one or more other boreholes are selected for placement of the geophones. The distance between source and phone boreholes is preferably a few hundred meters; distances of a kilometer or more are feasible but will not permit as much detail (spatial resolution) in the tomographic output as will closer spacings. The positions of the boreholes at depth should be known.

Geophones are then lowered into the selected borehole(s) and clamped to the wall. The phone spread should cover the zone of interest and extend some distance above and, if possible, below this zone. Spacing between phones or phone groups will depend on the resolution sought; for maximum resolution, the spacing should be only a few meters. The phones are connected through multiconductor cables to high-frequency amplifiers, digitizers, and recorders on the surface.

A series of small explosive charges are lowered into the source borehole. These are detonated individually at a series of shot points covering the zone of interest and extending above, and if possible below, this zone. For maximum resolution, the shot points should be spaced only a few meters apart. This requirement can probably be relaxed somewhat without much loss in resolution. Geophone recordings are obtained for each shot.

The recorded signals are then processed. The records are run through a digital high-pass filter. The direct arrivals are picked, with the aid of a computer program which sorts out the direction of arrival, utilizing also comparison of the records for each axis if 2-axis geophones are used, signal strength and character, and any available information from well logs and cores. The times of the direct arrivals are input to a tomographic reconstruction program, which, on the assumption of straight-line ray paths, finds a first-cut velocity distribution over the section between source and phone boreholes. This velocity distribution goes to a ray-tracing program which provides more accurate ray paths. Output of the ray-tracing program is fed back to the tomographic program, and iteration continues until a final velocity diagram or image is obtained, together with a consistent set of ray paths. Amplitudes of the selected arrivals may then be input to the tomographic program, which now produces an attenuation diagram or image of the section.

The velocity and attenuation images, such as those simulated in Figure 7-2, are run through digital image-processing programs to reduce noise, enhance edges, etc. They are compared with data from well logs and cores and whatever other pertinent information may be available. They are then interpreted in terms of reservoir heterogeneities: the position, in the section between the boreholes, of boundaries between beds, shale streaks (if not too thin), faults and fractures, sandbars, old stream beds, reefs, gas-liquid interfaces, variations in porosity or lithology that affect the acoustic properties, etc.

F. PERFORMANCE

On the basis of the discussions in Appendix D, a reasonable expectation for the resolution of a seismic tomography system appears to be 2 m for a hole-to-hole distance of 300 m, and 8 m for a distance of 1 km. Reasonable also is detection of velocity differences indicative of interfaces between beds of differing lithology, of gas-liquid interfaces, and of porosity variations of perhaps 5%. The attainable sensitivity to attenuation differences, and the significance of these differences, are more difficult to evaluate at this time, but gas/liquid interfaces should be detectable.

G. AEROSPACE CONTRIBUTION

JPL is familiar with the technology of tomography and is actively

engaged in other applications of it. Also, the preferred form of output will probably be images (pictures) displaying the velocity and attenuation distribution over the section in terms of brightness and color. JPL has extensive experience and expertise in digital image-processing and display.

H. COSTS

Once the technique is developed, field operations costs should be comparable to those for the more expensive kinds of well-logging: perhaps $10,000-$15,000 per borehole. Processing costs should be similar to or somewhat greater than those for a similar quantity of seismic data: a few hundred dollars.

I. ADVANTAGES AND DISADVANTAGES

1. Advantages

(1) Should provide detailed high-resolution data on the position and certain characteristics of reservoir inhomogeneties between boreholes.

(2) Should permit determining position of large induced fractures, if used before and after fracturing.

(3) Should permit determining position of gas/liquid front or interface in fire or steam floods.

(4) As compared to reflection seismography from the surface, should permit higher resolution and eliminate effects of weathered, highly absorbing, or highly reflecting near-surface layer. Should also provide information on attenuation, permitting estimate of some physical properties.

2. Disadvantages

(1) Requires multiple downhole phones and sources and multiconductor cable.

(2) If used between boreholes, gives information only on the section between the boreholes.

(3) If used between 1 borehole and the surface, coverage of reservoir and resolution are likely to be reduced.

J. DEVELOPMENT NEEDED

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1. Points Needing Further Attention

(1) Ability to cope effectively and efficiently with alternative paths.

(2) Obtaining good attenuation data despite focussing and defocussing.

(3) Downhole equipment and operational procedures.

2. Development Sequence

A suitable first step in development of the technique would be computer simulation, using signals generated for various models by, for example, a modified "synthetic seismogram" program. This would give an indication of the problems of handling alternative ray paths and focussing, and aid in preliminary selection of data processing procedures.

The next step would probably be one or more downhole tests using, to the maximum feasible extent, existing equipment. Data processing programs might be developed at this stage. The results would indicate possible performance and deficiencies in equipment, field operations, data processing, display, and interpretation.

Next would come design and development of improved (prototype) equipment, field operations, data processing, display and interpretation procedures for additional downhole tests. Results would probably indicate further needed improvement.

These improvements would be incorporated in a version of the system intended for commercial use. This system, after fabrication and test, would be released for such use.

K. FINDINGS

Hole-to-hole seismic tomography has considerable promise as a technique for detecting and defining reservoir inhomogeneities, for determining the position of induced fractures, and for determining the position of gas/liquid interfaces during fire or steam flooding. Small explosive charges could be detonated in cased or uncased boreholes and the resulting seismic signals detected by phones in another borehole several hundred or a thousand meters away. Tomographic data processing could potentially provide spatial resolution of 2-8 meters, varying with the hole-to-hole distance. The output would probably be in the form of images in which the velocity and attenuation distribution over the section would be displayed. These would be used for interpretation in terms of reservoir inhomogeneities, fracture and interface positions, and other characteristics of interest.

SECTION 8

DETERMINING OIL SATURATION, PERMEABILITY, POROSITY, AND OTHER RESERVOIR PROPERTIES

CONCEPT: A side-hole drilling device is lowered down a borehole to the zone of interest. It drills one or more slim holes at right angles to the main bore and extending several yards out. During this drilling, the main borehole is packed off; the side-hole drill uses filtered fluid from the formation as its drilling fluid. The system permits measurement and sampling outside the volume affected by drilling mud or by drilling the main hole. It can take core and fluid samples, can place logging tools in the side holes, and can apply a pressure differential between 2 side holes to permit measuring vertical or horizontal permeability in situ. By sweeping between 2 side holes, mobile and immobile oil contents, relative permeabilities, and effectiveness of surfactants can also be measured in situ.

A. PROBLEMS ADDRESSED

Many of the problems cited as important by the industry and DOE sources contacted in Phase 1 of the study concern measurements of reservoir properties. Knowledge of these properties is essential for proper reservoir assessment and reservoir engineering.

Among the needs mentioned were well cores that are more representative of the reservoir conditions, better measurements of residual oil saturation, measurements of porosity and oil saturation away from the boreholes, and more representative and less costly measurements of permeability, including vertical permeability. Core properties are changed by drilling, by exposure to drilling fluids, and by the temperature and pressure changes associated with transferral to the surface. Well log measurements are also affected by the drilling and especially by the drilling mud. Flow tests and production history indicate certain reservoir properties, but not with high accuracy. Vertical permeability is particularly difficult to determine accurately.

B. TECHNICAL METHOD AND PROCEDURE

The proposed method is based on the use of a drilling package which is lowered into the borehole and then drills one or more small-diameter holes several yards out, at right angles to the main bore. This then permits measurement and sampling out beyond the zone affected by drilling the main hole and by the drilling mud.

The machine is conceived as a long tubular enclosure containing various pumps, motors, and feed mechanisms. It would be lowered into the borehole to the desired level, and fixed in the desired position with a packer located at each end of the enclosure to seal out borehole fluid. Reservoir fluid would be drawn in, filtered, and pumped to the drill head for cooling and chip flushing. The side-hole would be drilled. If desired, a core could be cut and stored. At the completion of the drilling operation, an instrumentation package could be placed in the side hole and would be available for subsequent data acquisition. The side-hole may itself be packed off, and fluid samples could be obtained from it. The sequence may be repeated for additional locations.

If several side-holes are drilled, spaced either horizontally or vertically, a pressure difference could be applied between them; by measuring the flow between the side holes, the horizontal or vertical permeability could be determined. By sweeping between side holes with solvents or other fluids, mobile and immobile oil contents and relative permeabilities could be determined and the effectiveness of surfactants, for example, could be tested.

C. DESIGN CONSTRAINTS

The baseline operating requirements are taken as:

Borehole or casing size...6 inches (15 cm)

Side-hole reach...6 to 8 feet (2 to 2 1/2 m)

Side-hole diameter...1 to 1 1/2 inches (0.25 to 0.4 cm)

Drilling time...4 hours maximum

Operating depth...10,000 feet (3000 m) minimum (deeper capability desirable)

Operating temperature...to 300°F (150°C; higher temperature capability desirable)

The baseline assumptions are:

(1) Hydraulic (or electric) power available.

(2) Length of mechanism is not restricted.

(3) Reservoir fluid available in adequate quantity and quality to act as a drilling fluid or a reasonable substitute may be used.

The primary obstacles dictating most of the design criteria are dimensional constraints, remoteness, and environmental conditions. The dimensional constraints require a folding or collapsing device with relatively long reach. The remoteness affects factors such as control,

feedback, power, and repair. The harsh environmental conditions are temperature, pressure, abrasive surroundings, mechanical shock and vibration. The considered design criteria include those listed in Table 8-1.

Table 8-1. Design Considerations

Size and configuration
Thrust and torque of drill
Rigidity
Repeatability
Penetration technique
Chip removal
Maintaining clean and clear hole
Detector placement
Retrieval
Lead wire management
Core retrieval and storage
Reliability
Ruggedness
Lubrication
Penetration device endurance
Alignment
Power requirement
Chamber pressure control

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D. DRILL

A first step in developing the concept was to look at the widest possible variety of drilling instruments and techniques. Much of the following discussion is based on Maurer (Ref. 8-1). Table 8-2 lists traditional and novel drilling techniques. The first two are the traditional drilling techniques, percussion and rotary, the remainder are the novel or the experimental techniques. Techniques 8-13 require very large energy inputs and work by heating the rock to spalling, fusion or vaporization temperatures. It was thought that in a fluid environment these drills would behave poorly and further investigation was dropped. On the remaining novel techniques 3 through 7, the following comments are made:

(3) Spark - Experimental only; has high energy requirements but may provide high rates.

(4) Erosion - Requires 10-20 times energy of conventional drills but may provide high drill rates; works best in low density fluids; experimental.

(5) Explosive - Works well under high pressures (shock waves) but only puts out as much power as conventional drills.

(6) Pellet - Works best in viscosities close to that of water; leaves residual material; experimental only.

(7) Ultrasonic - Not proven for use at high pressure.

Based on the limited information available and the fact that no novel drill has a marked superiority over conventional drills, only percussive and rotary drills were looked at in detail. An additional factor in this selection is that a mechanical concept satisfactory for percussion or rotary drilling would typically be adaptable for most of the novel techniques, but the reverse is not true.

The following are key characteristics related to the use of conventional drills:

Common to percussive and rotary

Differential pressure (between drilling fluid and strata) greatly affects penetration rate because of chip removal factor.

Viscosity is important to hole stability, pressure surges, etc.

Percussive only

Frequency of oscillation, impulse load on bit, rotation rate and tip design are very important factors, and design parameters should be variable for optimum performance in a variety of drilling situations.

Table 8-2. Drilling Techniques

1) Percussion (jackhammer type)
2) Rotary (roller drag, drag, diamond)
3) Spark
4) Erosion
5) Explosive
6) Pellet
7) Ultrasonic
8) Plasma
9) Electric (heater, arc)
10) Laser
11) Electron beam
12) Microwave
13) Induction

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The only static thrust that the drill string must maintain is that which is lost in momentum transfer to the rock and to advance the drill.

The drill string mechanism must withstand repeated impact thrust loads.

Rotary only

Thrust imparted to bit is most important factor in penetration rate.

Rotary speed is the second most important factor in penetration rate.

A rotary drill string must be torsionally stiff or twisting (storing strain energy) will occur which when released may cause bit tooth failure.

On the basis of these considerations, and noting particularly the problem of devising an adequate side-hole drill string and drive mechanism to handle the impact thrust loads imposed by percussive drilling, a rotary drill was selected as tentative first choice.

The next step was to consider whether adequate power can be supplied to provide satisfactory drilling rates in the rock types to be drilled. These will primarily be reservoir rocks: sandstones and limestones.

In drilling practice (Maurer, Ref. 8-1), sandstone is considered soft (compressive strength <500 kg/cm^2) and limestone medium to hard (500-2000 kg/cm^2). These categories do not take into account porosity or the presence of water and oil in the matrix, which should make the rock easier to drill in most cases. To get a feel for how much power the drilling process might require, the basic drill rate equation and some numbers from Maurer are used below:

$$R = eP_o/AE$$

Where:

R = Drilling rate (cm/min)

P_o = Power output (joules/min)

A = Hole cross section (cm^2)

E = Specific energy (joules/cm^3)

e = Overall efficiency of power transmission source to rock

Assume a drill rate of 8 ft/hr (4.06 cm/min) and a 1 inch diameter hole (area = 5.07 cm^2) for a conventional drill in hard rock at atmospheric pressure (perhaps the worst case). A specific energy of 260

joules/cm^3 might be required. Using the drilling rate equation:

$$P_o e = (4.06)\ (5.07)\ (260) = 5352 \text{ joules/min} = 0.12 \text{ hp}$$

If a conservative efficiency of 25 percent is assumed (approximately the product of the rock drill efficiency, 30 percent, and the transfer efficiency, 80 percent) the total power requirement is:

$$P_o = 0.48 \text{ hp}$$

For a roller drag rotary drill approximately 3 times more energy is required but it is questionable as to whether a 1 inch diameter roller bit can be made with a comparable efficiency. Drag bits, diamond, and others are available that should be satisfactory for this application.

On this basis of this cursory analysis, the power required for side-hole drilling is low and could be easily obtained in a 6-inch diameter borehole with, for example, piston type aircraft hydraulic motors. Providing this power with a motor fitting into a 1-inch diameter side hole would be more difficult. A tentative choice was therefore made to place the rotary drive motor in the main borehole rather than at the drill head.

E. DRILL DRIVE SYSTEM

Significant preliminary study was done on the mechanics of the drive system and several mechanical devices were investigated to some detail. Among those studied (Figure 8-1) were:

Flexcoil booms made of collapsible, coilable tubing.

Extending chain saw devices.

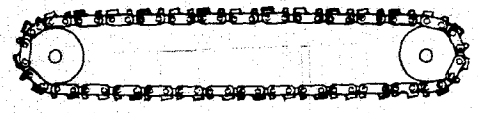
Arms made of magazine-fed cartridges.

Booms of cable-locked links.

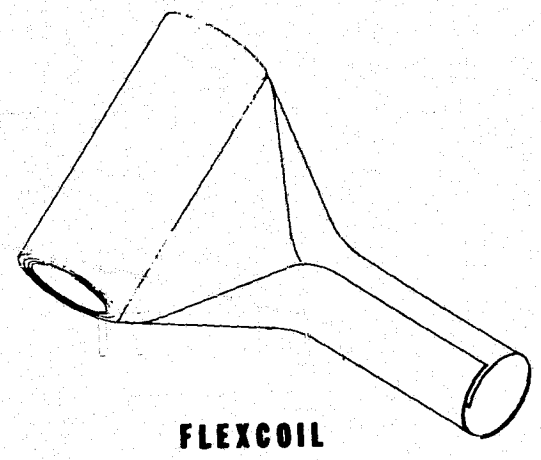
Interlocking rigid segments.

The approach that shows greatest promise and is recommended for further study is that based on interlocking rigid segments. Figure 8-2 is a conceptual layout of this configuration.

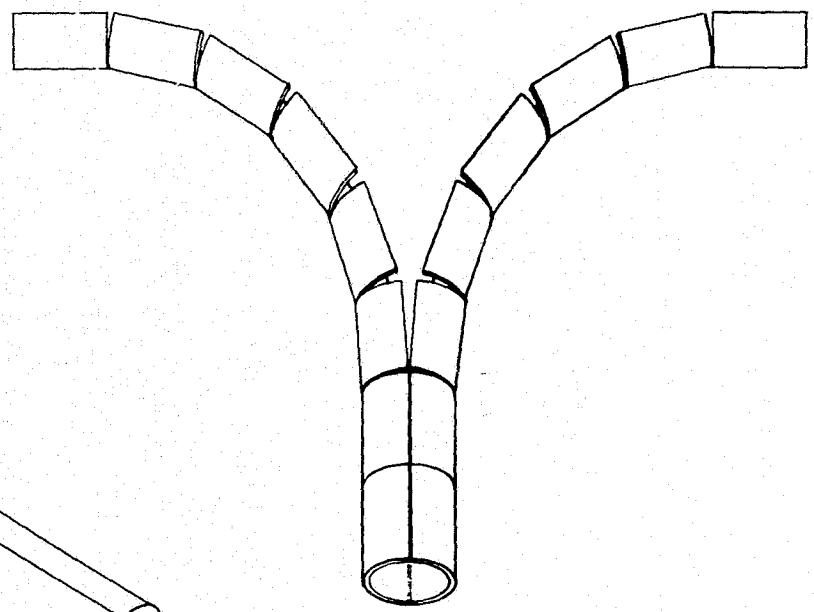
The primary element in this concept is a longitudinally split cylindrical rigid link (see Figure 8-3). A hinged chain is made up of these. Two of these chains lock together to form a rigid bar. This provides an expandable hollow rigid drive system capable of supporting high thrust loads. The thrust is provided by an external worm gear system to transmit the force directly from the wall of the drill mechanism to the rigid bar. Wipers clean any debris from the worm and gear upon retraction. The rigid bar is keyed to prevent rotation and does not rotate with the drill bit.



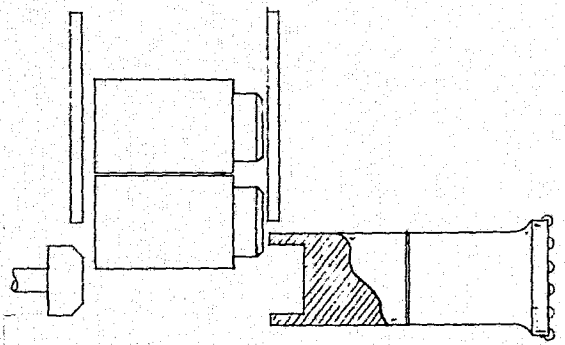
EXTENDING CHAINSAW



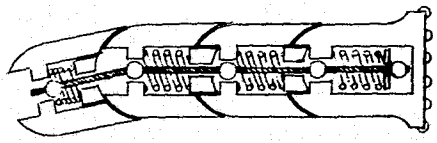
FLEXCOIL



INTERLOCKING RIGID SEGMENTS



MAGAZINE FED CARTRIDGE



CABLE LOCKED LINK

Figure 8-1. Possible Approaches for Drill Drive System

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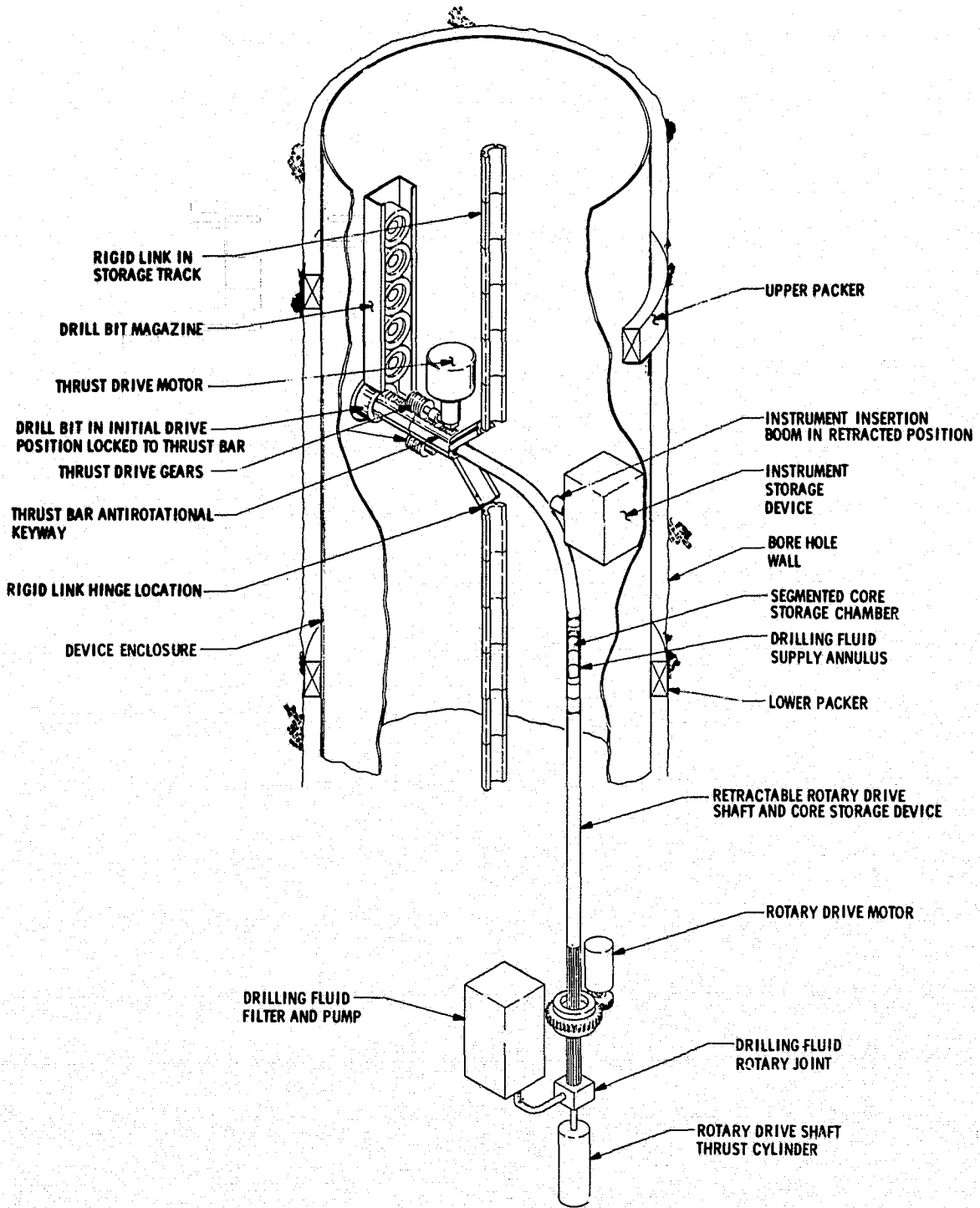

Figure 8-2. Side-Hole Drilling Device, at Commencement of Drilling

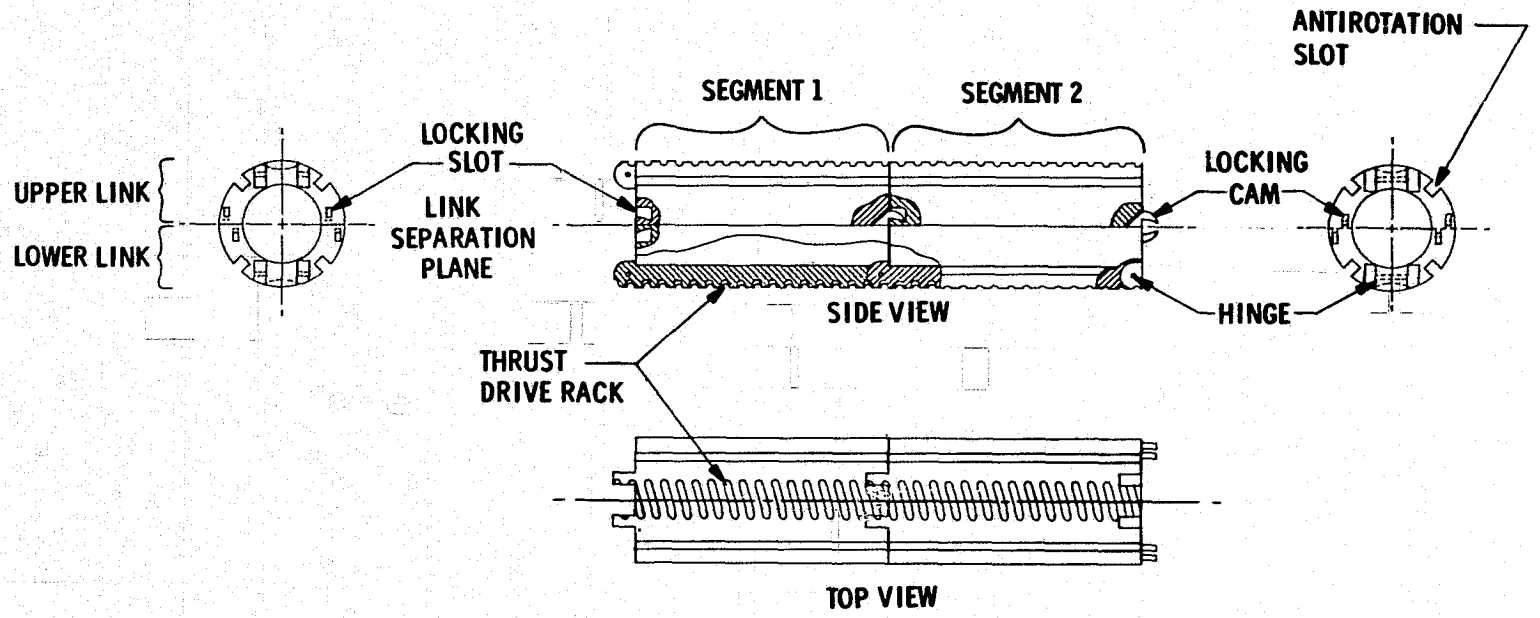

Figure 8-3. Rigid Links. Two Segments (Each Composed of 2 Rigid Links)

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A magazine containing drill bits is situated on the exit side of the system. These bits can be replaced downhole. This replacement will provide not only backup for damaged bits but also will allow the choice of optimum bits for the immediate task, i.e., an optimum bit for steel casing, for cement, or for rock. Each bit contains a thrust bearing to permit rotation against the rigid bar.

The bit is rotated by a rotary drive shaft fitting within the rigid thrust bar. This shaft is a hollow flex torsional device (Figure 8-2). Drilling fluid is pumped through the shaft to the drill head. The drive shaft also collects and stores core material, when desired. There is a separate drive shaft for each hole to be cored. Ribs are provided within the tubular shell of the drive shaft to allow passage of drilling fluid around a core (Figure 8-4). The forward end of the shaft has a core-catcher and a locking socket device which locks to the drill bit to provide drilling torque and also locks the bit assembly to the thrust bar A thrust cylinder permits advancing and retracting the rotary drive shaft when it is unlocked from the bit.

F. POWER SUPPLY AND CONNECTIONS TO THE SURFACE

Power for the side-hole drilling device could be either hydraulic or electrical. If downhole logging or pressure sensors are included, an electric cable will be needed for these. If the only sensors are those monitoring drill operations, their signals could be transmitted to the surface either electrically or by pulsing over a hydraulic line.

Hydraulic power is desirable for some of the downhole functions. Providing a pressurized hydraulic line from the surface is probably the method of choice. An alternative is to provide electric power via cable, and incorporate an electrically-driven hydraulic pump in the drill package. Electrical cables have tended to be more troublesome downhole than hydraulic lines.

G. FLUID AND PRESSURE HANDLING

Two fluid handling systems would be incorporated in the device. One, the hydraulic drive system, would be filled with clean hydraulic fluid and sealed. The other, the drilling-fluid system, which includes the body of the enclosure, would be closed while the assembly is being lowered down the borehole, to keep mud out. During this time, a bellows or diaphragm would equalize pressure inside and outside the housing. After the assembly is at proper depth and the main-bore packers set, the drilling-fluid system would be opened to the borehole. Drilling fluid would be obtained from the surrounding formation by pumping out the fluid between the packers. To flush, this would be dumped above the top packer. To drill, the fluid would be filtered and directed into the rotary drive shaft. A parallel stream could be directed to help clean the worm and gear drive.

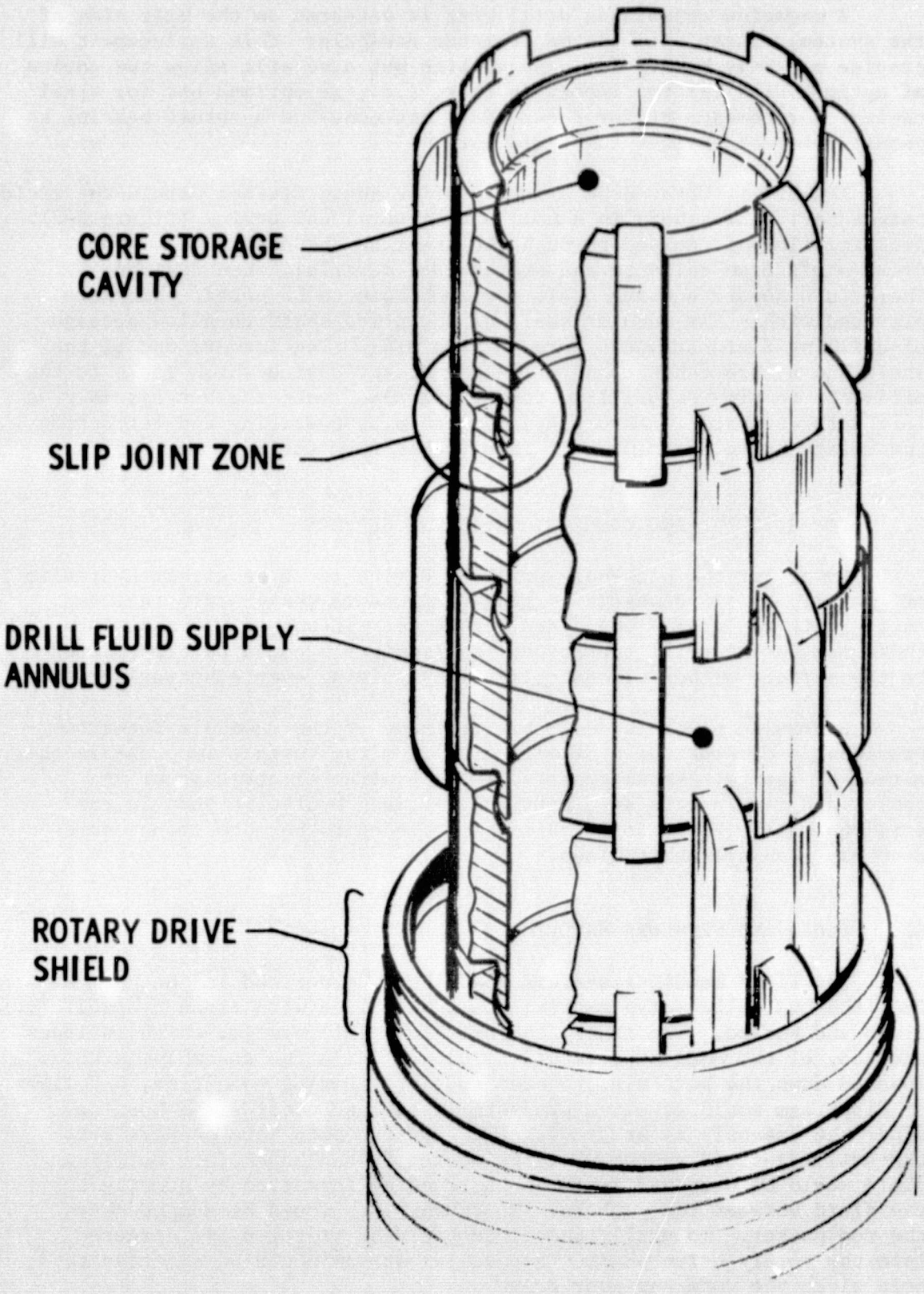

Figure 8-4. Rotary Drive Shaft

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H. INSTRUMENTS

An instrument storage system can insert one or more instruments into the side hole (Figure 8-5). These could be small-diameter electrical or nuclear logs, pressure and flow gages, fluid samplers, or packers. They may be left in place while other holes are being drilled by the side-hole device, as long as the housing remains fixed to the borehole wall, and can be retrieved with side-hole wire lines (Fig. 8-6).

I. OPERATING SEQUENCE

(1) Device lowered to desired depth.

(2) Packers set.

(3) Drilling port opened.

(4) Device interior and annulus around device flushed with reservoir fluid.

(5) Drill bit inserted in position from magazine.

(6) Link bar system advanced to engage with drill bit.

(7) Rotary drive shaft moved into position and advanced to engage bit and lock bit to link bar.

(8) Coolant pump provides drilling fluid.

(9) Drive shaft rotates and link bar advances by means of thrust drive system.

(10) Drilling continues to desired penetration.

(11) Link bar and drive shaft withdrawn from hole.

(12) Drive shaft withdraws from link bar, unlocking drill head from link bar.

(13) Bit drops into used-bit storage.

(14) Drive shaft withdrawn to storage position.

(15) Instrument storage and insertion system places instrument package in end of drill hole.

(16) Instrument is turned on.

(17) Link bar assembly moved to new position to repeat process.

If a coring bit is used, the core is produced (divided into short lengths) in step 10. In step 14, the core is withdrawn to storage position. Another drive shaft is used for any subsequent core drilling

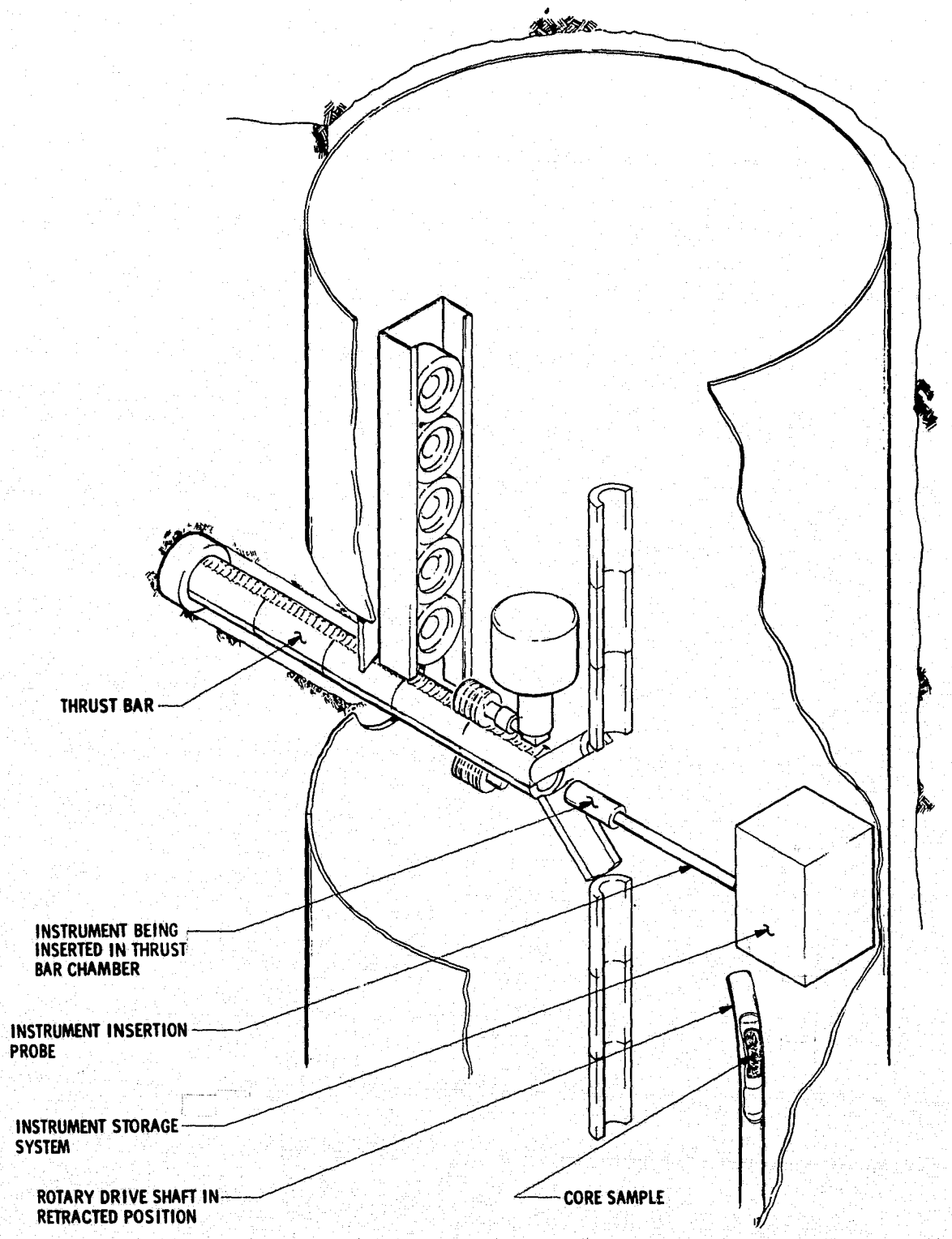

Figure 8-5. Instrument Insertion With Side-Hole Drilling Device. This sketch shows optional sequence in which bit is left at end of hole and instrument inserted before thrust bar is withdrawn. Alternative sequences permit removing bit, thrust bar, or both before inserting instrument.

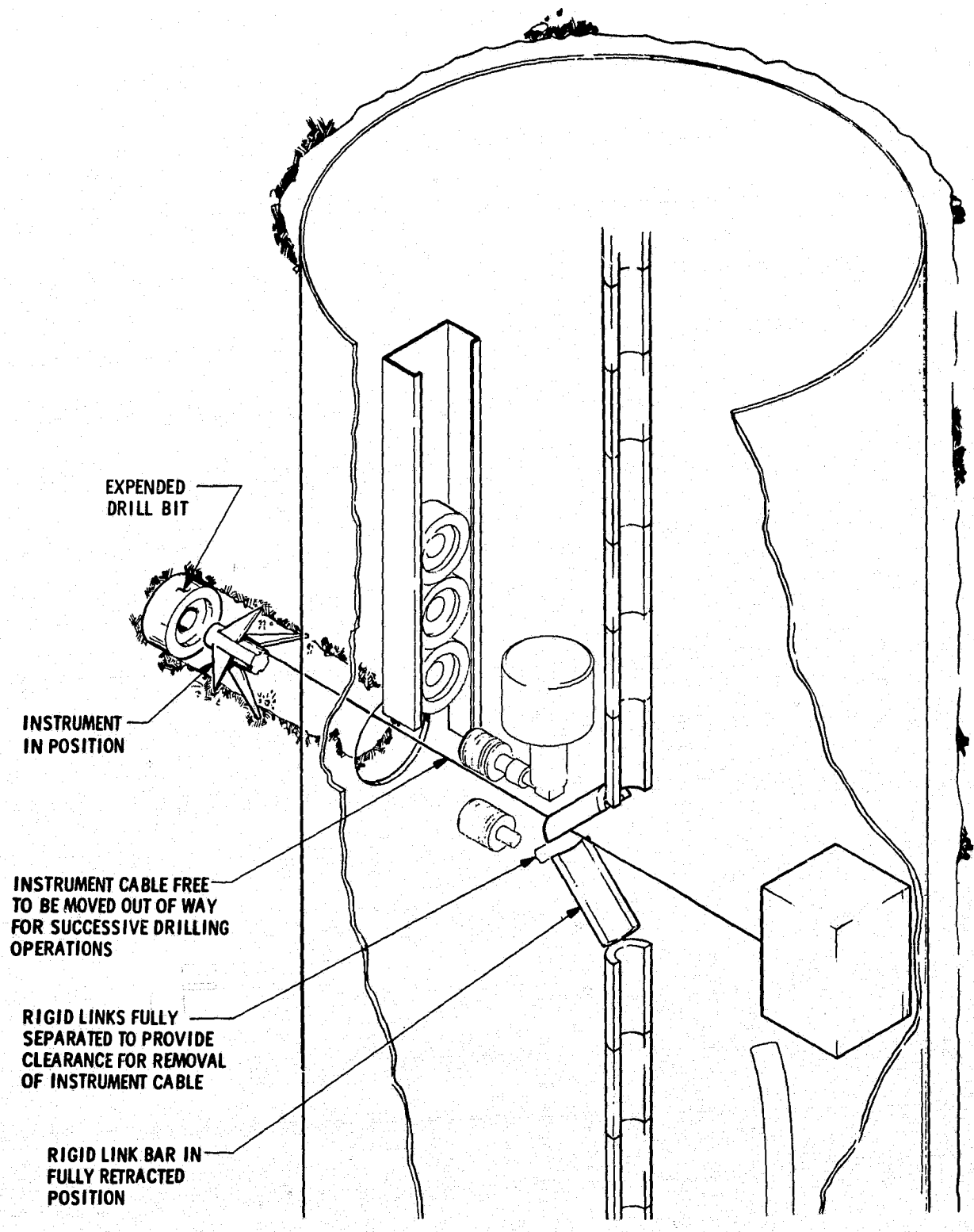

Figure 8-6. Side-Hole Drilling Device With Instrument Placed in Side-Hole. Instrument may be left in place while link bar mechanism is moved to drill another hole. Sketch shows alternative in which bit is left at end of hole. Other sequences permit removing bit before instrument is placed.

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during the same "trip" of the side-hole device.

Alternative sequences are possible. For example, after step 10 (drilling), the bit may be unlocked and left in the end of the hole, the drive shaft withdrawn, and an instrument inserted within the link bar (Fig. 8-5). The link bar is then withdrawn, leaving the instrument in place (Fig. 8-6). This could facilitate placing the instrument.

Still another alternative would be to remove the drive shaft, link bar, and bit, store the bit, reinsert the link bar, insert the instrument, and withdraw the link bar. This helps place the instrument and does not leave a bit at the end of the side hole.

J. ADVANTAGES AND DISADVANTAGES

1. Advantages

1) The concept permits logging, sampling, and other well testing outside the zone affected by mud and by drilling of the main bore.

2) Permits direct, in situ, measurements of both vertical and horizontal permeability, in a few hours.

2. Disadvantages

1) Provides logging at only a few depths.

2) Would probably require development of instruments to fit in side holes.

K. DEVELOPMENT NEEDED

Development of the side-hole drilling device could be divided into 3 phases:

Phase 1 activity would consist of a detailed design analysis which would include a more detailed model of the rock parameters and the design of a drill. The design would include component selection, detail design and a side drill model capable of drilling oil-bearing rock at surface pressures. Selection of the type of power would also be addressed. A working laboratory model would be built which would demonstrate rock drilling at normal atmospheric pressures. A reasonable amount of test time would be included in Phase 1. Phase 1 is estimated to require 18 months, and to cost about $300,000.

Phase 2 would follow the successful completion of Phase 1 and would consist primarily of iterations to improve the Phase 1 design and the design, fabrication and testing of a full scale working side-hole drilling machine capable of functioning at the prescribed operating depth.

Phase 3 would produce and test the final device for regular field use, capable of drilling, placing sensors, and recording the required reservoir information.

L. AEROSPACE CONTRIBUTION

The aerospace contribution to the proposed device includes expertise in mechanical design, in design and testing for operation under severe conditions, and in systems engineering.

M. FINDINGS

A side-hole drilling device would provide a method for obtaining data on permeability, porosity, and other reservoir properties, without interference from drilling mud or other effects of drilling the main hole.

Measurements in situ of vertical as well as horizontal permeability can be included. In situ measurements of mobile and immobile oil content, relative permeabilities, and the effectiveness of surfactants can be made.

The device would also permit obtaining fluid and rock samples outside the zone affected by mud or main-hole drilling.

Design and development of such a device appears technically feasible.

SECTION 9

PERFORATING DEEP HOLES, AND DEEP INTO THE FORMATION

Concept: An assembly of side-hole drills is lowered to the zone of interest. It drills several holes at a time, through the casing and cement if present, and as far as desired into the wall, up to a maximum penetration of 8 to 25 feet. Sensors record the penetration depths. The drills are then retracted and the assembly may be moved a short distance to drill additional holes.

A. PROBLEMS ADDRESSED

Mentioned by members of the industry as important problems were obtaining good penetrations into the formation in deep wells, including penetration deep into the formation. The standard techniques of firing bullets into the wall or using shaped explosive charges become less effective as the depth increases, for two reasons. First, the static pressure in the well must be subtracted from the gas pressure produced by the propellant or explosive charge to give the effective pressure; the effective pressure is considerably reduced in deep wells. Second, the diameter of the well bore and casing generally decreases as the depth increases; this in turn restricts the size of the charges that can be used. Thus, standard perforation techniques lose reliability in deep wells. For example, the casing may be perforated but not the cement or surrounding rock.

If the well produces poorly after perforation, it is difficult to diagnose the problem. Is the poor production due to poor perforation or to a poor reservoir? This important distinction is difficult in practice, because with standard perforating techniques there is no way to tell how deep or how clean a perforation has been obtained.

In addition, perforations deep into the rock may be desired in tight formations, particularly tight gas sands or shales, as a preliminary to fracturing. Liquid explosive may be placed in the deep perforations and detonated to produce fractures extending a good distance out from the main borehole. For massive hydraulic fracturing, it is possible that by packing off the borehole at several different depths, fractures could be initiated from deep perforations going in different directions. This might permit obtaining several massive fractures in one reservoir from a single borehole.

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B. TECHNICAL METHOD AND PROCEDURE

The proposed method is based on use of a drilling package which

is lowered into the borehole and then drills multiple small-diameter holes several yards out at right angles to the main bore. The package could operate in both cased and uncased portions of the bore.

The machine is conceived as a long tubular enclosure containing various pumps, motors, and feed mechanisms. It would be lowered into the borehole to the desired level, and fixed in the desired position with slips. Well-bore fluid would be locally filtered and circulated to the drill heads. Four side-holes would be drilled simultaneously at 90° horizontal spacing. Vertical spacing would be at 4 foot centers. Sensors would indicate the penetration depth of each side hole.

When the desired side-hole penetration is reached, the drilling strings are retracted. With the slips still locked in place, the drilling assemblies are rotated through a selected angle and the drill sequence repeated. After side-holes have been drilled at various horizontal angles as desired, the slips are released and the assembly may be raised or lowered as desired, the slips reset, and additional holes drilled at other depths. These may be above or below the first set of 4 depths or may be interpolated between individual levels drilled in the first operation.

C. DESIGN

The basic design of the device would be like that of the side-hole drill described and illustrated in Section 8, with the following major differences:

(1) Four drill assemblies, interlaced, would be provided, rather than a single assembly.

(2) The mud or other fluid present in the main borehole would, after filtering, be used as the drilling fluid, and the drilling package would be open to this fluid.

(3) No provision for obtaining core or fluid samples and no provision for placing instruments would be included.

(4) The penetration depth of the side holes may be increased to about 25 feet (8 m), if desired.

As with the device described in Section 8, provision may be included to use a steel or cement drill bit to penetrate the casing or cement, then change to a rock bit for continuing penetration.

D. QUANTITATIVE CHARACTERISTICS

The baseline characteristics of the device are considered to be:

Overall length of device	30 feet (9 m)
Borehole or casing size	5 inches (12.7 cm) minimum
Side-holes simultaneously drilled	4
Horizontal spacing of side holes	90°
Vertical spacing of side holes	4 feet (1.2 m)
Side-hole reach	Nominally 8 feet (2.5 m). May be extended to 25 feet (8 m) by increasing the vertical spacing of holes simultaneously drilled.
Side-hole diameter	1 1/4 inches (3.2 cm)
Drilling time to 8 feet (2.4 m)	1 hour usually, 2 hours maximum
Operating temperature	To 300°F (150°C; higher temperature capability desirable)

With the characteristics listed, if, for example, 2 sets of holes are drilled with drilling assemblies rotated 180° between sets, the hole pattern produced would be 8 holes in diametrically opposed pairs at 4 foot intervals, each with up to 8 feet of penetration. More closely spaced holes could be produced by repeatedly rotating the assembly through a smaller angle between drilling operations, then lowering the device 1 or 2 feet and repeating.

The basic 4 foot vertical spacing and 8 foot penetration were arbitrarily selected. These might be modified to meet specific requirements. With the design contemplated, the vertical spacing between drills will be at least half the desired side-hole penetration. If, for example, 2 foot penetration is considered adequate, the device could be designed with 1 foot vertical spacing between drills. If, on the other hand, a 25 foot penetration capability will be needed, the vertical spacing of the drills will be 12 1/2 feet. If the capability of drilling 4 holes simultaneously is to be retained, the latter change would require increasing the overall length of the drilling device to about 60 feet.

E. COST

The cost of perforation services with the device described has not yet been estimated. Costs should be less than with the instrumented device covered in Section 8 of this document, because the perforating version would not include provision for control of drilling fluid composition, for core or fluid sampling, or for instruments to measure reservoir properties. Costs will, however, be higher than for shaped-charge or bullet perforations.

F. ADVANTAGES AND DISADVANTAGES

1. Advantages

(1) Permits perforation a significant depth into the formation.

(2) Provides definite indication of the depth and diameter of each perforation.

(3) Should provide clean holes, free of plugging.

(4) Can provide very deep perforations (up to 25 feet (8 m)) if desired.

(5) May provide a basis for more efficient explosive fracturing or for obtaining multiple massive hydraulic fractures in a reservoir from one borehole.

2. Disadvantages

(1) Will be more expensive than perforating by bullets or shaped charges.

(2) Will be slower than perforating by bullets or shaped charges.

(3) Will be limited in maximum operating temperature until seals are developed for higher temperature service.

G. DEVELOPMENT NEEDED

A development program similar to that outlined in Section 8 is suggested. Development of instruments to measure reservoir properties and means to place these instruments would not be included, however.

H. AEROSPACE CONTRIBUTION

The aerospace contribution to the proposed device includes expertise in mechanical design, in design and testing for operation under severe conditions, and in systems engineering.

I. FINDINGS

A multiple-side-hole drilling device would provide a method for reliably obtaining perforations into the formation even in deep wells. The depth and diameter of each perforation would be known. If the well subsequently fails to produce as expected, this would remove an important source of uncertainty as to the reason.

The device would also permit perforation penetrations up to 25 feet (8 m) if desired. In addition to possible direct increases in flow,

such perforations could aid subsequent fracturing by allowing placement of liquid explosive to a greater horizontal extent within the formation or by permitting, with suitable packing techniques, production of several massive hydraulic fractures in the reservoir from a single well.

Design and development of such a device appears technically feasible.

SECTION 10

DOWNHOLE PRESSURE MEASUREMENTS AT HIGH TEMPERATURES

Concepts: Two types of downhole pressure measurement systems are proposed. Both types would provide readings continuously available at the surface, without delay, and with no need to apply corrections for temperature. For service to 525°F, a system utilizing a variable capacitance gage is suggested. This system would use downhole electronic components qualified for operation at 525°F. For temperatures to 600°F or higher a system utilizing a resistive sensor is suggested. This would incorporate vacuum-sputtered thin film strain gages in a bridge circuit and would not require other downhole electronics.

A. PROBLEMS ADDRESSED

Downhole pressure measurements with high accuracy, high sensitivity, and high stability are needed for a variety of reservoir engineering purposes. Among these are pressure draw-down and build-up tests, hole-to-hole pressure transient tests, flow tests, interference tests, injection tests, monitoring of primary and enhanced recovery operations, and others. The total pressures are high, up to 15,000 psi (10^8 Pascals), and the pressure changes to be measured are small, often less than 1 psi (10^4 Pascals). Moreover, these changes may take place slowly, over periods of weeks. These characteristics set difficult requirements for sensitivity, accuracy, and stability.

Deep petroleum reservoirs, especially gas reservoirs, and those in areas of high geothermal gradient, often are hotter than 300°F (150°C). Moreover, there are large known resources of heavy oil for which thermal recovery methods (steam injection or fire-flooding) are used or under consideration. Borehole temperatures of 500°F (260°C), and occasionally 600°F (315°C) or higher, occur in these operations. Thus, there is a need for downhole pressure measurement systems combining the sensitivity, accuracy, and stability of the best present downhole devices with the capability of operating at considerably higher temperatures.

Some pressure measurement systems record downhole; the recording device must be brought to the surface to obtain the data. Other downhole systems provide continuous real-time recordings at the surface. Surface recording is desirable to permit continuous monitoring of reservoir tests and operations.

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For some types of borehole measurement, such as fluid density vs depth, it is desirable to move a pressure gage along the borehole, measuring pressure vs depth. In this application, quick response is desirable. Not only must the pressure reading respond quickly, but if the pressure sensor is sensitive to temperature, the device must reach temperature equilibrium quickly to avoid errors due to transient temperature gradients.

The best existing commercial downhole systems with an operating range up to 300°F (150°C) have a stated accuracy of 0.025 percent of full scale with a sensitivity of 0.005 percent of full scale. One exception to sensitivity is the Hewlett-Packard quartz crystal gage for which a sensitivity of 0.00009 percent of full scale is claimed (Ref. 10-1).

The best existing system with an operating range to 600°F (315°C) is claimed to have accuracy of 0.2 percent and sensitivity of 0.05 percent of full scale. It uses a multi-turn Bourdon tube sensing element and downhole recording. None of the surface recording types has an operating temperature exceeding 300°F (150°C).

All of the commercial systems are temperature sensitive to some extents and the downhole operating temperature is measured in order to make a correction. Although very good, the quartz gage is quite temperature sensitive and its signal is converted to pressure by computation using temperature as a variable. It will not provide readings in a varying temperature environment as it requires a thirty minute stabilization time.

Several organizations are already working on development of highly sensitive, highly accurate pressure gages for high temperature downhole use (Refs. 10-2 to 10-5). Most of this work is supported by DOE; some of it utilizes aerospace technology. Nevertheless, another look seemed worthwhile, emphasizing use of aerospace technology and development of a complete system, not only of a gage. The system would include such other elements as amplifiers, cables, recording equipment, power supply, operating and maintenenace procedures, etc.

B. TECHNICAL METHOD AND PROCEDURE

Two different approaches are suggested for further consideration. One uses a variable capacitance sensor, in the geometry shown in Fig. 10-1. Downhole electronics are necessary with this sensor, and these limit the operating temperature. It appears that an adequate set of electronic components should be available to permit operation up to 525°F (275°C) (Refs. 10-2 and 10-6).

For higher temperature capability, an approach using resistance strain gages is suggested. The strain gages would be vacuum-sputtered thin film. Figure 10-2 shows the proposed geometry. No downhole electronics would be required, except for the strain gages themselves and connecting wiring. The device should operate satisfactorily to 600°F or higher.

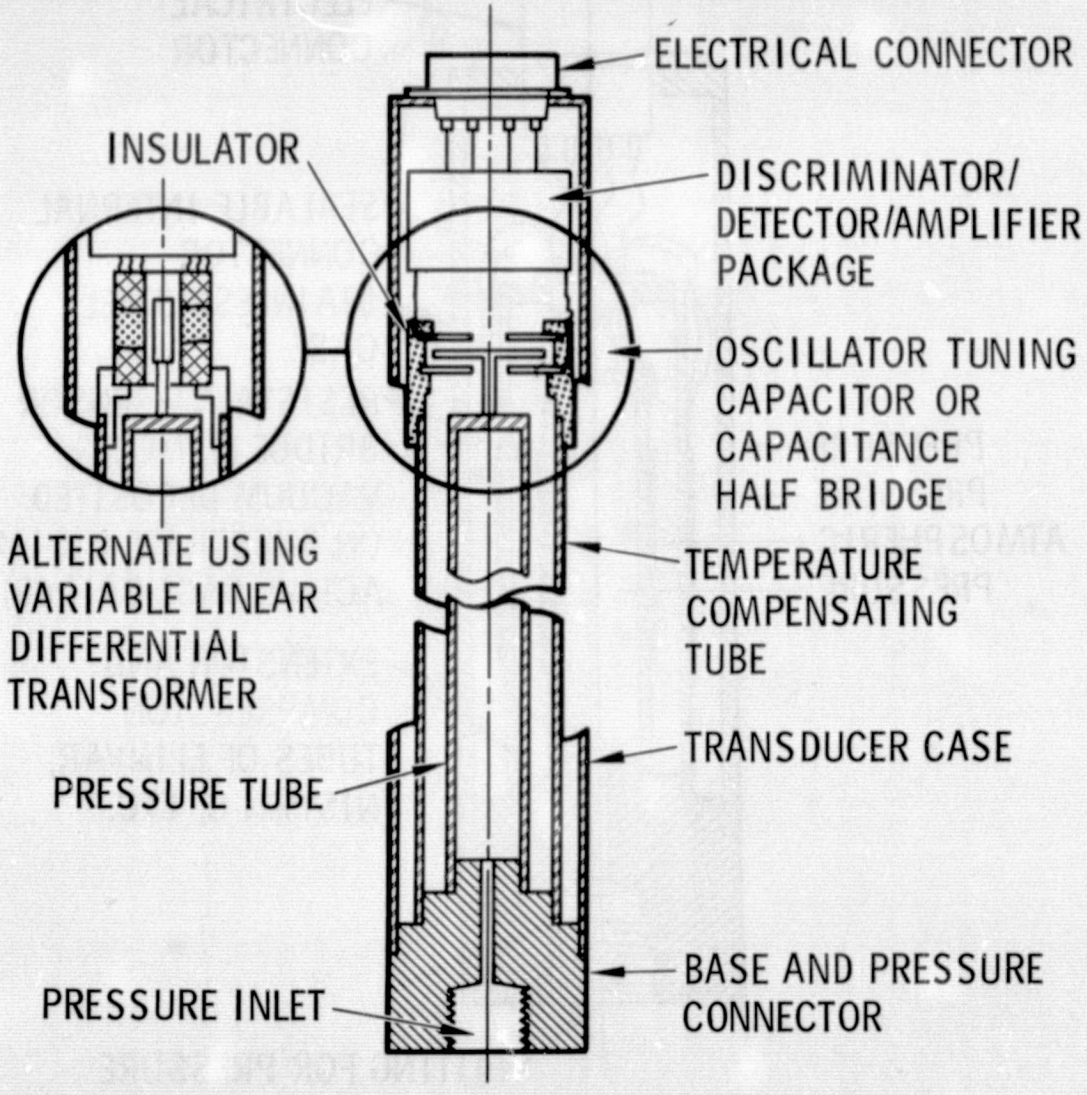

Figure 10-1. Reluctance-Type Pressure Gage for Downhole Measurements

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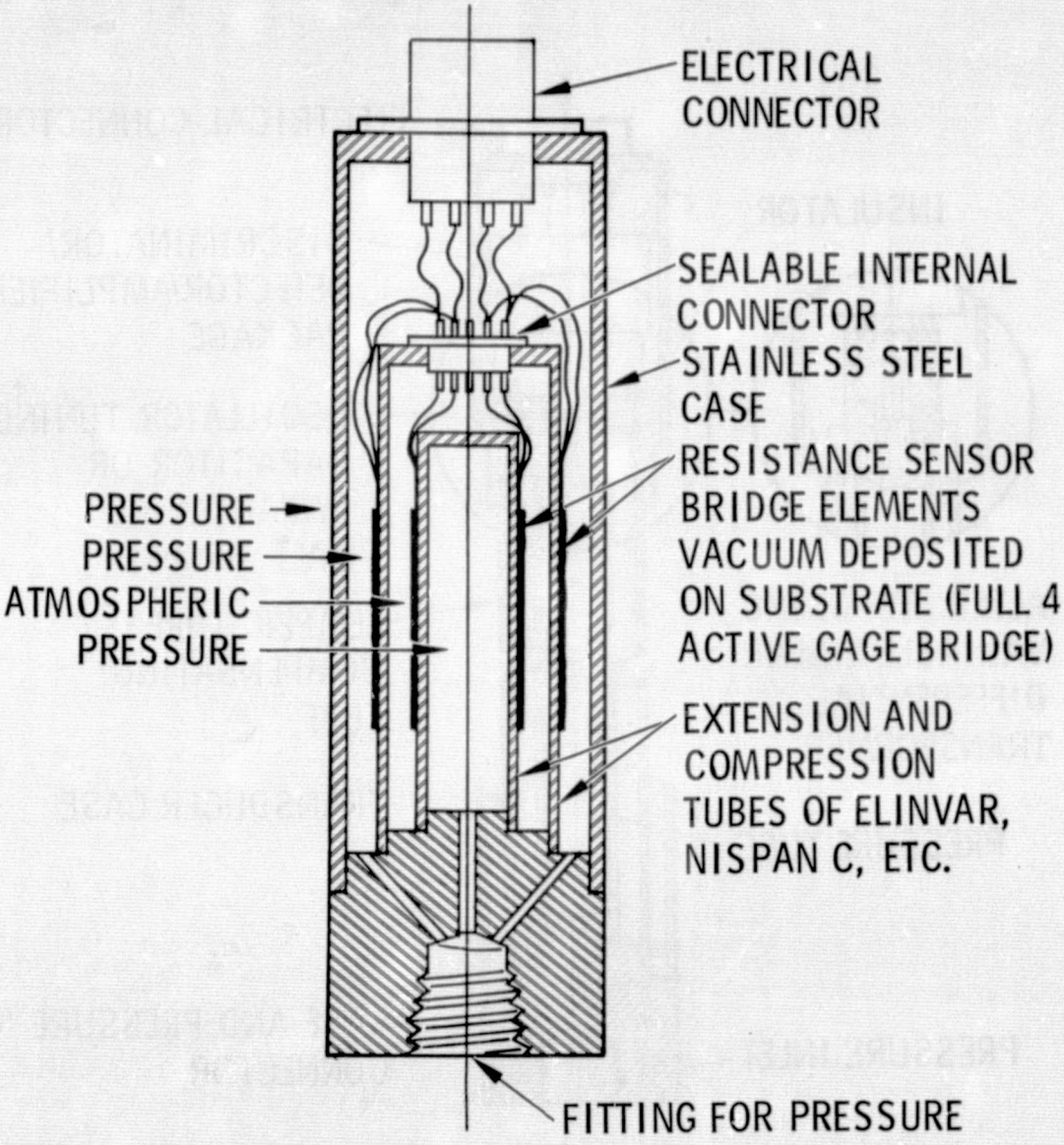

Figure 10-2. Resistance-Type Pressure Gage for Downhole Measurements, Using Full Bridge of 4 Active Strain Gages

Both of these designs measure pressure through the relative movement of 2 concentric tubes. One tube is pressurized, the other is not, but both are in the same temperature environment. Relative movement between them is induced by pressure but not by ambient temperature. The resulting systems are insensitive to temperature.

To provide surface readout, both approaches use electrical cable to the surface.

C. DESIGN REQUIREMENTS

Proposed requirements for the pressure measuring system are:

(1) Operating temperature range to 500°F (260°C). (Preferable is 600°F (315°C).

(2) Absolute accuracy of 0.02% of range.

(3) Precision (short time repeatability) 0.01% of range.

(4) Long time stability 0.01% of range per month.

(5) Sensitivity 0.005% of range.

(6) Pressure range preferably up to 15,000 psi (1000 bars).

(7) Lower ranges selectable, from 3000 psi (200 bars) up.

(8) Surface readout and recording in real time.

(9) No manual corrections for temperature required.

(10) Response time to specified accuracy not over 2 minutes.

(11) Operable at least 1 month downhole.

(12) Not damaged by rapid pressure and temperature changes.

(13) All elements of system retrievable and reuseable.

(14) Diameter of downhole elements 1.5 inch (3.8 cm) or less.

D. APPROACH

The approach used to arrive at the proposed sensing systems was to suggest a number of alternative concepts, evaluate these against the requirements, and examine some of the trade-offs.

Areas given most consideration include the use or non-use of downhole electronics, which trades off with downhole cable problems, and the choice among various types of sensors.

F. DOWNHOLE ELECTRONICS AND DATA TRANSMISSION

Both downhole cables and electronics have been troublesome at high temperatures. The usual downhole cables have 1 or 7 unshielded conductors. With low-level output from the downhole sensor, attenuation along the cable and pickup from the power leads may introduce serious errors. Use of large diameter shielded conductors in the cable could reduce these difficulties. If downhole electronics are employed, a much higher level signal can be supplied to the cable and telemetry methods, such as FM or digital encoding, can be employed to greatly reduce effects of cable attenuation and pickup. However, very few electronic components are yet available for use above 575°F (300°C); even for 575°F the selection is somewhat limited (Ref. 10-6). Circuits containing multiple components have been tested successfully at 575°F for 100 hr only (Ref. 8-6). To assure the 1 month of downhole operation desired, it appears that the maximum operating temperature of downhole electronics should be limited to 525°F (275°C). If this temperature is satisfactory, systems using downhole electronics may well be preferable. For higher temperature use, a system without downhole electronics must be chosen for the present. Development of electronic components and assembly techniques for use at higher temperatures is under way utilizing several different approaches (Ref. 10-7), but it will be some years before they will be considered available for commercial use.

At 500°F (260°C) and above, cable design and construction is also a problem. However, cable for use at higher temperatures is claimed to be available (Ref. 10-8); in any case, cable satisfactory at 600°F (315°C) appears nearer than development of an adequate variety of electronic components for this temperature.

Use of other methods for transmitting data uphole can be considered as alternatives to a cable. Acoustic or hydraulic pulses are examples. It appears, however, that all of these alternatives would in practice require downhole electronics. Thus, they would be limited to use at 525°F (275°C) or below, and do not seem to offer much advantage over a cable.

G. SENSORS

To meet the requirements for precision, accuracy, stability, and sensitivity, it is important that the pressure sensor be free from mechanical hysteresis, creep, and temperature sensitivity. Types of sensors examined in this study include Bourdon tube, vibrating crystal, magnetic force balance, and variable capacitance, inductance, and resistance devices. These will be discussed one by one.

1. Bourdon Tube

Existing Bourdon tube gages normally record downhole and must be retrieved to obtain the data. They are made of a material (such as "Ni Span C") which has a very low temperature coefficient of modules

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of elasticity and a very low temperature coefficient of expansion. Nevertheless, it is usual to measure the peak downhole temperature and use it to correct the readings obtained. It may be desirable to temperature — compensate the Bourdon tube by mounting it on a rotating base with a high temperature coefficient; the base would rotate counter to the direction of thermally induced changes in the Bourdon tube. To verify the usefulness and economics of such a modification to the existing design, the inconvenience and inaccuracies caused by not compensating would need to be investigated.

Bourdon tube gages can meet a 600°F (315°C) temperature requirement. They do not, however, meet the requirement for surface display and recording in real time. Redesign to add remote display might be possible but would probably require use of downhole electronics, so a 600°F requirement would then not be met.

2. Vibrating Crystal Sensor

A vibrating crystal whose frequency varies with the applied force is the basis of a widely used low temperature downhole pressure sensor (Ref. 10-1). Efforts are underway both to upgrade this gage for use at 525°F (275°C) (Ref. 10-3), and to develop other forms of vibrating crystal pressure gage for downhole use at high temperatures (Ref. 10-5). In view of this work elsewhere, it did not seem worthwhile to address the same concept in this study.

3. Magnetic Force Balance

In this type of sensor a magnetic force balance is used to oppose the force caused by the pressure to be measured. The current required to hold a fixed position or balance is directly proportional to the force. If a sufficiently sensitive device (such as a variable impedance detector) is used to detect motion of the system, only a small error signal is required to cause a current change adequate to maintain position balance. The value of current required will then be a measure of the applied pressure. One of the advantages of the force balance method is that it is free of hysterisis. It can be made very sensitive and is free from temperature effects.

The magnetic force balance requires downhole electronics and is accordingly restricted to temperatures lower than 525°F (275°C). More important, it appears suited to very low pressures, and not to the high pressures encountered in downhole measurements.

4. Variable Reluctance Sensor

A design is suggested in which the pressure produces a strain difference, in the form of elongation, between two tubes, one of which is a closed pressure tube and the other a temperature compensating tube (see Figure 10-1). The tubes are mounted to a common base; the relative motion of their far ends is determined by the pressure.

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The relative motion of the tube ends may be transduced into an electrical signal by mounting a capacitance plate on the end of each tube. This capacitor may be used to vary the frequency of an oscillator. If the sensor is properly designed the heterodyne or difference output frequency is linearly or near-linearly proportional to the applied pressure, and very insensitive to temperatures.

Alternatively, a capacitance plate may be mounted on the end of one tube between 2 plates mounted on the other tube. It is then possible to construct a capacitance bridge with 2 active legs which is very insensitive to temperature and to motion perpendicular to the axis of the tubes. As another choice, a variable linear differential transformer may be used as the transducer.

In this type of sensor the length of the tubes and the resolution of the electrical transducer determine the pressure sensitivity. The material characteristics of the tubes determine the temperature compensation, the variation of sensitivity with temperature, and the hysteresis. Elinvar or a suitable ceramic may be used.

The variable reluctance sensor appears to have some excellent characteristics for the downhole use but requires downhole electronics. If development of a system limited to 525°F (275°C) appears worthwhile, this type of sensor should be considered further.

5. Variable Resistance Sensor

This sensor, like that just described, employs a closed pressure tube and a temperature compensating tube, mounted to a common base. The electrical transducer is a set of resistance strain gages. Figure 10-3 shows a simple form of this design. Here 2 strain gages are active and 2 are used for temperature compensation in a full 4-gage bridge circuit. The resistance strain gages are vacuum sputtered thin film. If the tubes are electrically conducting , they are precoated with a silicon monoxide or alumina substrate, onto which the film is sputtered. This technique permits the strain in the underlying material to be accurately measured and is superior to other methods of applying resistance strain gages (Ref. 10-9). Material on which the strain gages are applied could include metals such as "Elinvar" and or "Ni Span C", which have very low temperature coefficient of modulus of elasticity as well as low thermal expansion and low mechanical hysteresis (Ref. 10-10), or fused silica.

Figure 10-2 is another version of the variable resistance sensor in which the temperature compensation tube provides strain to 2 resistance gages in compression. These are used in a full bridge of 4 active gages and provide sensitivity double that of the design in Figure 10-3.

Sputtered resistance gages are suitable for temperatures extending well above 600°F (315°C) and can be used without other downhole electronics. They appear to be the method of choice if operating at temperatures up to 600°F is to be provided utilizing technology now commercially available.

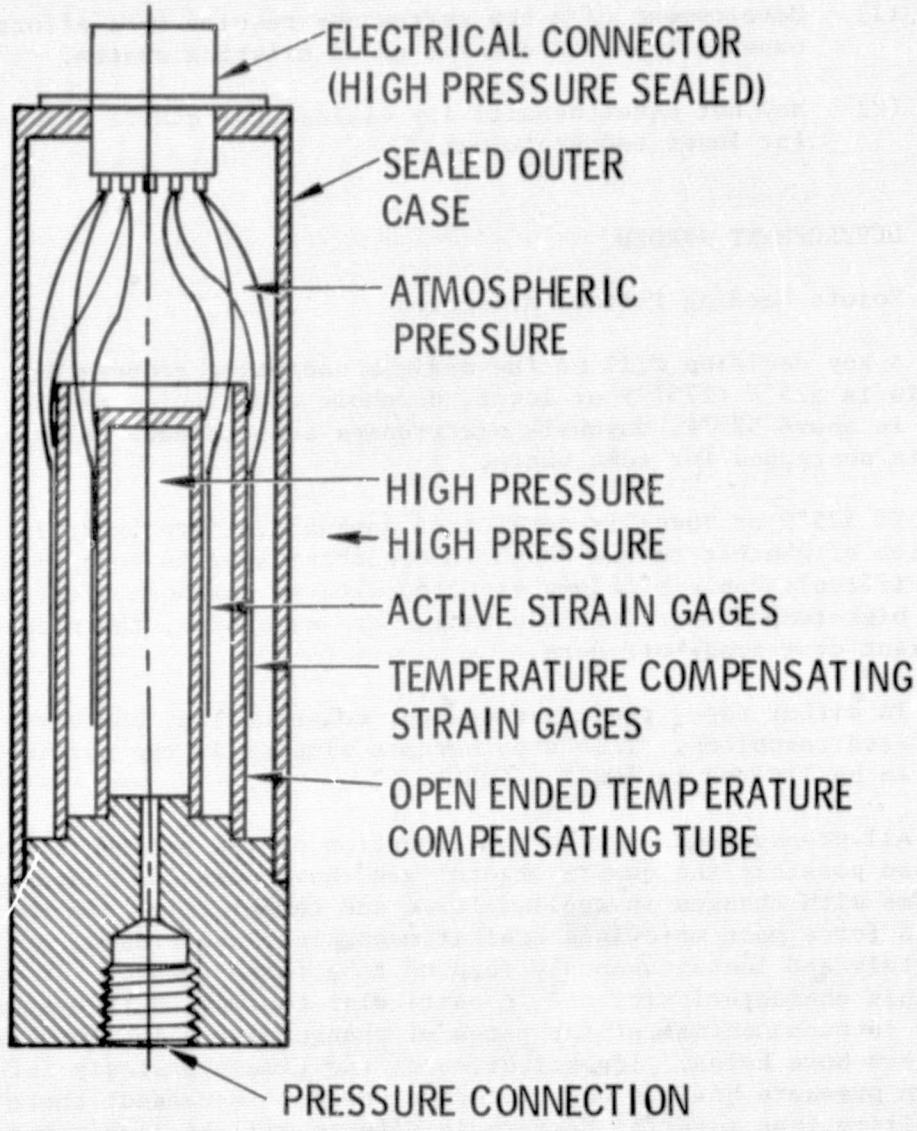

Figure 10-3. Resistance-Type Pressure Gage for Downhole Measurements, Using Bridges of 2 Active and 2 Compensating Strain Gages

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H. ADVANTAGES AND DISADVANTAGES

1. Advantages

(1) Would combine capabilities of high temperature operation (500°F to 600°F, 260 to 315°C) with immediate accessability of data at the surface.

(2) Would provide rapid response ($\leq$ 2 minutes).

2. Disadvantages

(1) Development of a new system may require more effort and expense than improvement of an existing system.

(2) May not equal sensitivity claimed for quartz crystal gage (at lower temperatures).

I. DEVELOPMENT NEEDED

1. Points Needing Further Attention

A key decision will be the maximum operating temperature required. If this is 525°F (275°C) or lower, downhole electronics may be used. If it is above 525°F, downhole electronics are excluded unless development is postponed for some years.

If 525°F or lower is considered adequate, there is still the decision of whether to use downhole electronics or to cope with the more difficult cable problems expected with no downhole electronics. Since high-temperature downhole cables are expensive, there is an important cost trade-off here.

In either case, the cable design, construction, and performance may present problems. This area becomes simpler if the service temperature can be limited to 500°F (260°C).

All pressure gages with the exception of the servoed force balance gage and possibly the quartz crystal gage have material characteristic problems with changes in applied force and temperature. In the case of applied force most materials exhibit mechanical hysteresis, or failure to completely and instantaneously respond to a force change. It is possible that this characteristic, and in particular thermoelastic hysteresis, may become inconsequential at the rates of change of applied force expected in petroleum bore holes. Investigation of the time-hysteresis interaction between pressure buildup and transducer output is needed; there is a good probability that material hysteresis effects will be inconsequential.

If resistance strain gages are chosen, the technique of depositing the resistive elements and the insulating substrate (if any) onto the particular material selected for the pressure and temperature compensating tubes need to be examined. This will be important in obtaining satisfactory sensor performance.

2. Sequence of Development

The first steps in development of the pressure measuring system should be establishing requirements and preliminary examination of the overall system, followed by design, fabrication, and test of breadboard sensor elements.

Subsequent steps would include design, building and test of a breadboard of the downhole electronics, if these are to be used, and design of the cable, followed by design, construction and test of a prototype system for evaluation downhole.

After the prototype is debugged, the operating version of the system could be designed, fabricated, tested, and put into use.

J. AEROSPACE CONTRIBUTION

Aerospace contribution to the proposed pressure measuring system includes extensive experience in design, fabrication, and test of sensors, including pressure sensors, and of remotely-reading sensing systems for accurate measurements over extended periods of time, under severe environmental conditions and where access to the device is not possible. Other pertient experience includes data transmission, environmental testing, and systems engineering.

K. FINDINGS

It appears feasible to develop a downhole pressure sensing system which can operate at temperatures up to 600°F (315°C), provide readings at the surface immediately, require no temperature corrections of these readings, have fast response, and meet the accuracy, sensitivity, and other requirements of reservoir engineering, assessment, and operation. It should be possible to do this using technology that is now available.

Two approaches that seem feasible for the transducer element of the pressure are a variable reluctance (capacitor or differential transformer) element or a resistance strain gage utilizaing vacuum-sputtered thin films. The variable reluctance approach requires downhole electronics. At the present state of the art, these are limited to 525°F (275°C). This temperature is probably adequate for the great majority of petroleum applications. Resistance strain gages can be used with or without downhole electronics, and should be satisfactory to 600°F (315°C) or more.

The use of downhole electronics has the advantage of simplifying the cable problems and probably of reducing cable costs. The desirability of using downhole electronics needs to examined in some depth.

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SECTION 11

REDUCING THERMAL STRESSES AND HEAT LOSSES IN CASINGS OF STEAM INJECTION WELLS

Concepts: Double-walled tubing with insulation between the walls is used for steam injection. Each length of tubing is prefabricated, complete with insulation; the tubing is run with standard couplings. Also, a little of the water normally fed to the steam generator may instead be fed down the annulus between the tubing and the casing.

A. PROBLEMS ADDRESSED

Current interest in steam injection oil-recovery methods is toward the use of deeper wells and higher pressure wet steam with correspondingly higher saturation temperatures. Particular problems are higher heat losses from the flowing steam to the surrounding rock, higher casing temperatures and thermal stresses, and packing failure because of the high temperature steam with the intrusion of steam, water, and oil at the well bottom into the annulus between the steam pipe and the casing. The problems become more severe as the well depth increases, and play a major role in limiting the depth at which recovery by steam injection is economic. If steam injection can be extended to depths significantly greater than the present economic limit of 1500-2500 feet (in most areas), very large amounts of heavy oil in known reservoirs would become economically recoverable.

Of primary concern for deep injection wells is the reduction of heat losses from the steam to the surrounding rock since this energy is not available for oil recovery in the formation below, and the cost of the oil recovered is thereby increased.

Also of concern is the avoidance of lateral deformation and buckling of the casing due to thermal stresses. Willhite and Dietrich (Ref. 11-1) estimated that the change in casing temperature for J-55 grade material (minimum yield stress 55,000 psi) is about 250°F for casing yield and about 500°F for joint pullout in tension during the cooling cycle following steam injection for a new well. However, allowable thermal stresses and thus allowable casing temperature changes are expected to be less for older wells often used for steam injection. Lack of uniformity of cement also can lead to local failure and buckling at lower temperature changes of the casing.

Casing problems can be reduced or eliminated by going to higher strength casing steels. This approach is not applicable to existing wells, adds something to the cost, and does not reduce the heat losses into the rock.

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To reduce both heat losses and casing stresses, it is usual, except in very shallow wells, to inject the steam through tubing rather than directly into the casing. The tubing is sometimes insulated. The insulation replaces all or part of the water that would otherwise fill the annulus between tubing and casing. A variety of solid, liquid, and gaseous insulations have been tried (Refs. 11-2 and 11-3).

Natural gas has been pumped down the annulus to provide gaseous insulation, and then injected into the formation with the steam. This appears to be too costly at expected prices for oil and natural gas (Ref. 11-2), and may be banned as a low-priority use of natural gas in the United States.

Replacing the water in the annulus by oil would also reduce the heat losses. Downhole packers fail quickly in steam injection wells; once the packer fails, water gets into the annulus (Ref. 11-3). A petroleum-base gel has been suggested, as less easily displaced than oil (Ref. 11-2), but also requires a down-hole packer.

Tests have been made of a liquid silicate, placed in the annulus, which is converted to a foamed solid by the heat of the steam (Ref. 11-3). It has proven difficult, however, to control the porosity, thermal conductivity, and thickness of the foam produced in this way. Also, the foam is mechanically weak and tends to break off during thermal cycling and when the tubing is pulled.

Strap-on solid insulation has also been considered. It too is mechanically weak. To reduce the damage, an outer pipe, placed over the insulation has been tried. This was welded to the tubing near the bottom of each length. The tubing ends were left bare for handling and coupling (Ref. 11-2).

None of these insulation techniques has come into general use.

B. APPROACH

A key point seems to have been generally overlooked in utilizing solid materials for insulation downhole: The thermal resistance of good solid insulators depends on pore spaces filled with a very poor thermal conductor: air or vacuum. If water gets into these pore spaces, the thermal resistance of the material is considerably degraded.

High temperature materials with very high thermal resistance generally consist of mineral or glass fibers with low packing densities, so that they contain a large volume of air. For downhole use they should be completely sealed off from water or other well-bore fluids. Further, the fiber assemblies are very weak and compress readily to greater packing densities. This increase in density (loss of pore space) also causes a major loss of resistance to heat flow. Thus, the materials should be kept free from mechanical loads, such as those imposed by well-bore pressures.

Another idea that apparently has not been considered for steam injection wells is circulating water through the annulus between the tubing and the casing to cool the casing and to pick up some of the heat that would otherwise be lost to the surrounding rock. Such a cooling method is common practice in liquid propellant rocket engines where some of the propellant is used to cool and maintain the integrity of the nozzle wall. In an injection well, the heated water would mix with the steam at the injection level and be injected into the formation with it. The loss in steam quality at the formation that might result could be counterbalanced by producing slightly higher quality steam at the generator. The use of coolant water flow through the annulus would obviate the need for a downhole packer and prevent intrusion of steam into the annulus.

C. TECHNICAL METHOD AND PROCEDURE

The method suggested for reducing heat losses and casing thermal stresses is based on the use of prefabricated double-walled tubing, with insulation sealed between the walls. In addition, the I.D. of the tubing may be reduced over that normally used (to provide room for additional insulation), and water may be run down the annulus. These concepts will be outlined in turn.

1. Sealed Insulation

The basic concept is the use of prefabricated lengths of double wall tubing with insulation sealed between the walls. The outer pipe would be cut to lengths a few inches shorter than the standard 30 or 20 ft length of the inner tube and assembled over the inner tube leaving exposed the coupling threads of the inner tube. Insulation, probably loose or matted glass or ceramic fibers, would be placed between the inner and outer tubes. A prestress would be applied between the two tubes. An end plate would then be welded at each end of the outer pipe, sealing it to the inner tube (Figure 11-1a). If desired, this plate could be made of low-conductivity high strength stainless steel and could be made in a rib-and-hollow fashion to reduce the heat leakage through the steel while providing strength, pressure tightness and corrosion resistance. It could also extend some inches longitudinally to further reduce heat losses (Figure 11-1b and c). The welds would be inspected to insure that they do not leak at downhole pressures. A standard coupling would be threaded onto the inner tube at one end of each length. Thread protectors could then be applied. All of this assembly would take place in a fabrication shop before the tubing is delivered to the oil field.

At the well, the individual lengths of tubing would be coupled together and run in the usual way. The outer pipe will protect the insulation from mechanical damage, leakage, and hydrostatic pressure. During steam injection, the insulation will greatly reduce heat loss to the casing and surrounding rock. By keeping the casing cooler it will reduce thermal stresses in the casing.

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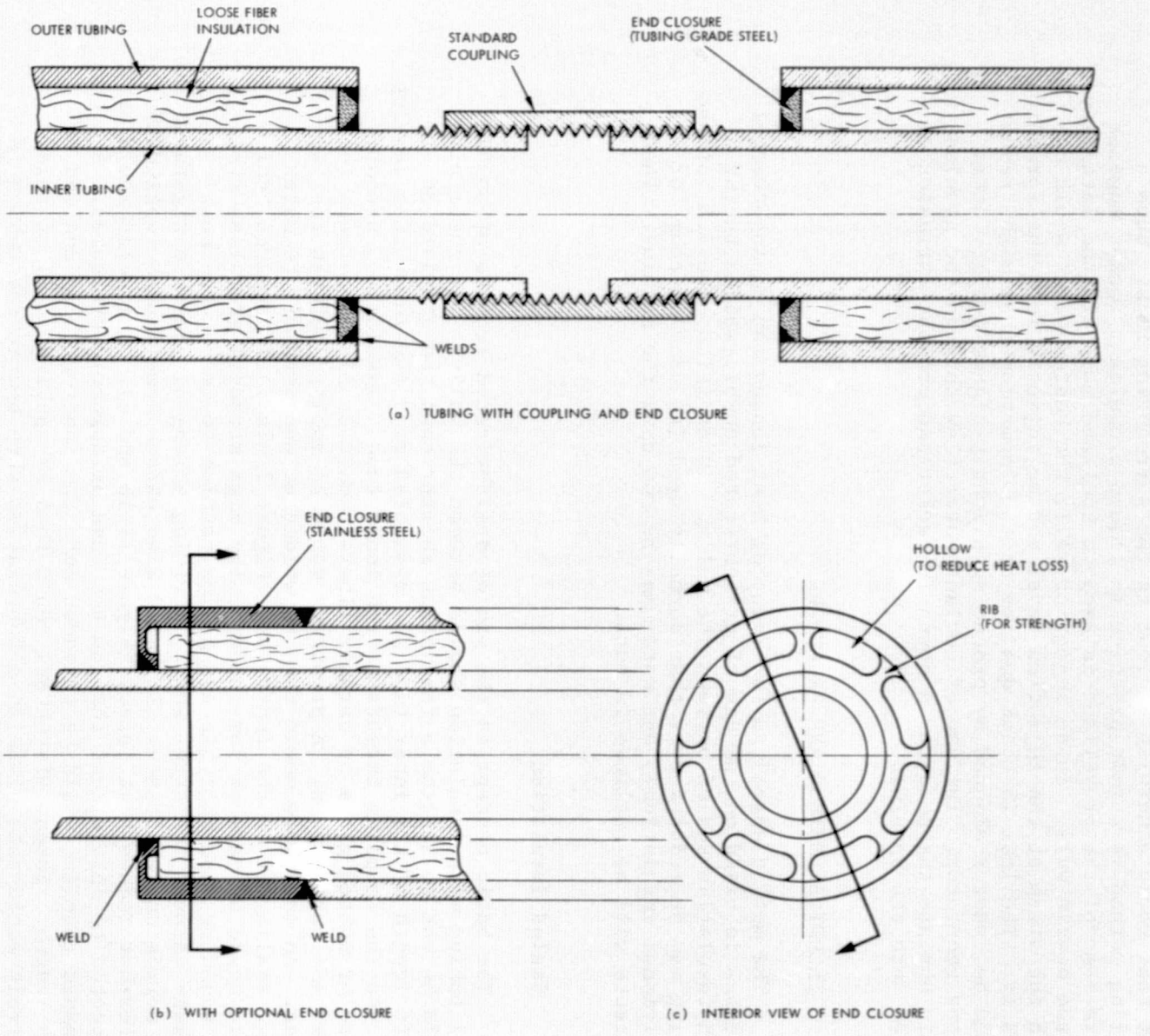

Figure 11-1. Insulated Tubing with Coupling

A method rather similar to this has been suggested by Volek and Pryon (Ref. 11-4). Their design, however, involved welding to the coupling, which may be questionable because of the distortion that may result. Also, with their design, if any leakage of the high pressure steam occurs along the threads, steam would get into the insultation and ruin it. They apparently contemplated use of insulation with considerably higher thermal conductivity than that suggested here, and did not suggest any special provisions, such as those mentioned above, to reduce the significant heat leakage that can occur through the steel end closures.

2. Couplings

Leaving the couplings bare entails a small increase in heat loss (Appendix G). It would be possible to strap split halves of rigid insulation over each coupling after it is made up, but the gain in performance may not be sufficient to justify complicating the procedure of running the tubing.

3. Tubing Size

Where possible, the size of the inner tubing should be kept small. With the size of the outer pipe wall limited by clearance from the casing, reducing the diameter of the inner wall can allow a considerable percentage increase in the thickness of insulation between the walls. This in turn will reduce heat loss and thermal stress in the casing.

4. Cooling Water in Annulus

A small amount of water may be run continuously down the annulus. This will cool the casing, and so reduce thermal stress in the casing. Also, since the casing will be cooler, it will lose less heat to the surrounding rock. At the injection depth, the water from the annulus will mix with the steam from the tubing and be injected into the formation. Thus, the heat picked up by the water is not lost but is transferred to the reservoir. The slight loss in steam quality caused by adding water at the injection depth can be counterbalanced, if desired, by slightly decreasing the amount of water fed to the steam generator. (If the heat supplied to the generator is held constant, the quality of steam leaving the generator will be slightly increased). Pumping water down the annulus provides control of the fluid in the annulus without need for a downhole packer.

D. DETAILED ANALYSIS

The concepts outlined are analyzed in detail in Appendixes E, F, and G.

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E. QUANTITATIVE CHARACTERISTICS

The reductions in heat loss and thermal stress possible by use of the techniques mentioned depend upon the depth of the steam injection zone, the reservoir pressure, the geothermal profile and thermal properties of the rock surrounding the well, the sizes of casing and tubing used, the thickness and thermal properties of the cement, the rate of steam injection, the temperature and quality of the steam, the injection time, and other variables. One example is treated in Appendix E. The properties assumed there include a depth of 2500 ft, a 9.6 in. borehole, 7 in., 26 lb/ft, casing, and 500 bbl water/day injected into the well as steam at 596°F and 70% quality. If the steam is fed directly into the casing, then after a week of injection all of the steam will condense in the borehole, and about 50% of the heat will be lost to the walls of the hole (Table 11-1).

The casing, if not prestressed, will yield during thermal cycling, regardless of casing grade used; J-55 grade casing may pull out at the joints on cooling. If the casing is properly prestressed, J-55 casing will yield and N-80 grade is marginal with respect to yielding; joint pull-out should not occur.

If the steam is fed through 2-7/8 in., 6.4 lb/ft, tubing and the annulus fills with stagnant water, the heat loss will be roughly 40%, the steam quality at the well bottom near 0%. The casing will still yield if not prestressed; H-40 grade may pull out at the joints; J-55 probably will not. If prestressed, J-55 may still yield; N-80 should not.

Suppose double-walled tubing is used, with the outer wall made from 5 in., 11.5 lb/ft pipe, and the space between the walls filled with insulation having a conductivity of 0.02 BTU/(hr-ft-°F). If the end closure is 0.25 in. thick and of material similar to the tubing, and if a 12-in length is left bare at each coupling, the heat loss is only 8.7%. The steam quality at well bottom will be 56%; thermal cycling will not cause casing yield or pullout.

If the end closure is hollowed out to an effective thickness of 0.1 in. and made of a suitable stainless steel, the heat loss is reduced to 6.9%. If instead 5% of the feed water is diverted from the steam generator to cool the annulus, or if the 12 in. length at each coupling is covered with strap-on insulation with a conductivity of 0.35 BTU/(hr-ft-°F), the heat loss will be 8.2%. If all these steps are combined, the heat loss will be 6.0%. Finally, if in addition the inner tube of the double-walled tubing is reduced to 1.9 in. O.D., the heat loss is only 3.3% and the steam quality at entrance to the formation rises to 64% (Table 11-1).

It is clear that in this example the use of insulation drastically reduced heat loss and thermal stresses in the casing and drastically increases steam quality at entrance to the formation. Reducing the tubing size from 2-7/8 in. to 1.9 in. or improving the design and material of the end closures further reduces heat loss. Diverting a little feed water to the annulus or insulating the couplings provides

Table 11-1. Heat Losses and Casing Temperature in Steam Injection Wells*

Injection Well Design	Heat Lost Along Bore %	Steam Quality at Entrance to Formation %	Maximum Casing Temperature °F
Depth 2500 ft., steam pressure at wellhead 1500 psia, injection time 7 days			
Steam fed in casing	~50	0	~596
Steam fed in 2-7/8 in. 6.4 lb./ft. tubing	~40	0	~470
Steam fed in double-walled insulated tubing:			
2-7/8 in. inner tube; 5 in. 11.5 lb./ft. outer pipe -			
End closure A*			
Bare coupling	8.7	56	173
Insulated coupling	8.2	57	169
End closure B			
Bare coupling	6.9	58	157
Insulated coupling	6.4	59	153
Same plus 5% of feedwater fed to annulus			
End closure A			
Bare coupling	8.2	57	169
Insulated coupling	7.7	57	164
End closure B			
Bare coupling	6.4	59	153
Insulated coupling	6.0	60	149
Steam fed in double-walled insulated tubing:			
1.9 in. inner tube, 5 in. outer pipe			
End closure A			
Bare coupling	5.7	61	146
Insulated coupling	5.2	62	142
End closure B			
Bare coupling	4.2	63	135
Insulated coupling	3.6	64	129
Same plus 5% of feedwater fed to annulus			
End closure A			
Bare coupling	5.2	62	142
Insulated coupling	4.8	62	138
End closure B			
Bare coupling	3.8	63	131
Insulated coupling	3.3	64	127
Depth 2500 ft., steam pressure at wellhead 1500 psia, injection time 30 days			
Steam fed in casing	41	0	~596
Steam fed in 2-7/8 in. tubing	~30	~15	~480
Steam fed in double-walled insulated tubing			
2-7/8 in. inner tube; 5 in. outer pipe,			
5% of feedwater fed to annulus			
End closure A			
Bare coupling	8.0	57	193
Insulated coupling	7.5	58	187
End closure B			
Bare coupling	6.3	59	172
Insulated coupling	5.9	60	167

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Table 11-1. Heat Losses and Casing Temperature in Steam Injection Wells* (contd)

Injection Well Design	Heat Lost Along Bore %	Steam Quality at Entrance to Formation %	Maximum Casing Temperature °F
Depth 2500 ft., steam pressure at wellhead 1500 psia, injection time 180 days			
Steam fed in casing	33	12	~596
Steam fed in 2-7/8 in. tubing	~25	~25	~490
Steam fed in double-walled insulated tubing			
2-7/8 in. inner tube; 5 in. outer pipe, 5% of feedwater to annulus			
End closure A			
Bare coupling	7.8	57	214
Insulated coupling	7.4	58	208
End closure B			
Bare coupling	6.1	60	188
Insulated coupling	5.7	61	182
Depth 1000 ft., steam pressure at wellhead 500 psia, injection time 7 days			
Steam fed in casing	16	51	467
Steam fed in 2-7/8 in. tubing	~12	~55	~350
Steam fed in double-walled insulated tubing:			
2-7/8 in. inner tube; 5 in. outer pipe			
End closure A			
Bare coupling	2.7	66	144
Insulated coupling	2.6	66	142
End closure B			
Bare coupling	2.2	67	130
Insulated coupling	2.0	67	125
Same plus 5% of feedwater fed to annulus			
End closure A			
Bare coupling	2.2	67	130
Insulated coupling	2.0	67	125
End closure B			
Bare coupling	1.7	68	118
Insulated coupling	1.6	68	116

*Calculated for the following conditions:

Borehole size 9-5/8 in.
Casing 7 in., 26 lb.
Cement conductivity 0.5 BTU/(hr.-ft.-°F)
Rock conductivity 1.4 BTU/(hr.-ft.-°F)
Rock diffusivity 0.04 $ft.^2/hr.$
Surface temperature 70°F
Geothermal gradient 0.0083 °F/ft.
Steam rate 500 bbl water/day (7250 lb./hr., including any annulus water)
Steam quality at wellhead 70% if all water goes to steam generator. (Heat input to steam generator held constant)
Insulation thermal conductivity 0.02 BTU/(hr.-ft.-°F) (between inner and outer walls of tubing)
End closure A: Thickness 0.25 in., conductivity 27 BTU/(hr.-ft.-°F)
End closure B: Thickness equivalent 0.1 in., conductivity 10 BTU/(hr.-ft.-°F)
Bare length per coupling: 12 in. each 30 ft.
Coupling Insulation: thermal conductivity 0.35 BTU/(hr.-ft.-°F)

Calculations given in Appendices E, F, and G.

a slight additional reduction in heat loss.

If the injection time is increased from 7 days to 30 or 180 days, the loss without insulation is reduced more than the (smaller) loss with insulation (Table 11-1). The inprovement possible with insulation is still very significant.

Table 11-1 also gives an example of a 1000 ft well with inlet steam at 500 psi. The heat loss without insulation is much less than in the deeper well, but insulation still significantly reduces heat loss and increases steam quality; moreover, it drastically reduces thermal stresses in the casing.

F. ECONOMIC EVALUATION

The above discussion suggests that, typically, in a 2500 ft hole about 20% of the heat could be saved by adding insulation to the tubing. At a heat rate of 7×10^6 BTU/hr for the well, the saving is 1.4×10^6 BTU/hr.

Assume this heat is supplied by burning crude providing 6×10^6 BTU/bbl. The saving is then 0.23 bbl/hr per injection well. Take the price of the crude at $11.50/bbl today, increasing 6%/yr due to inflation. The savings per well are 2.68/hr or $24,000/yr before inflation. If the tubing will be used for 10 yr, this amounts to $240,000/well, plus inflation.

Assuming that the cost of money is 16%/yr, of which 6% is due to inflation, the present value of the fuel savings (5 yr average use of money at a money cost of 10%, after cancelling out inflation) is 160,000. To this should be added the saving of 35% the capital cost of the steam generator system, at 6,000 per million BTU/hr. This is estimated as $9,000. Thus, the present value of the cost saved is $170,000/well, or $68/ft of tubing. For a 30 ft length of tubing, this is $2,000.

This amount is then available to cover increased costs of materials, fabrication, and transportation of the tubing. The added cost of steel, at 11.5 lb/ft for the example used, will be about $4/ft. and of the insulation, at 0.2 lb/ft, less than $1/ft. Fabrication and transportation should hardly cost the $1,900 savings remaining per 30 ft length.

Any increased cost of maintaining the insulating tubing over that of maintaining bare tubing needs to be considered. This is, however, probably more than compensated by the savings in maintenance and other labor on the 20% of steam generating capacity that is not needed.

Thus, the use of the insulation method proposed should provide a substantial cost saving for a typical 2500 ft injection well. Since the heat saved increases rapidly with depth, the cost savings should be even greater for deeper wells.

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For a 1000 ft well, with steam injected at 500 psia, the heat savings is estimated as about 7%. The present value of the savings in fuel and in capital needed for the steam plant amounts to $58,000/well, equivalent to $58/ft or $1700 per 30 ft length of tubing. This should be ample to pay for the increased cost of tubing and leave a net savings. The method should therefore be economical even for shallow injection wells.

G. ADVANTAGES AND DISADVANTAGES

1. Advantages

(1) Reduction in fuel needed to generate steam.

(2) Increase in steam quality at entrance to the formation.

(3) Reduction in casing thermal stresses and in likelihood of casing and cement failures.

(4) Reduction in capital cost and maintenance cost of steam generator equipment, since less steam is needed.

(5) Should increase the depth at which steam stimulation is economically practical, and thus make additional large quantities of heavy oil economically recoverable.

(6) May obviate the need for a downhole packer in steam injection wells and associated packer failures.

(7) In new wells may sometimes permit the use of lower strength steel casing.

2. Disadvantages

(1) Increased cost of tubing.

(2) Unfamiliarity of field crews with the special tubing.

(3) Resulting somewhat slower running and pulling of tubing.

(4) Possible somewhat higher maintenance cost of tubing.

H. DEVELOPMENT NEEDED

1. Points needing further attention:

(1) Design and fabrication of end closures to minimize cost and provide high reliability.

(2) Handling thermal stresses in the tubing. Calculation indicates that yielding under thermal stresses should usually be prevented by use of grade N-80 tubing and prestress between the inner and outer tubes prior to welding the ends.

(3) If cooling water is run down the annulus, how is it to be handled at well bottom? One could simply leave a length or two of tubing uninsulated at the bottom of the string to preheat the water, then let it mix with the steam at the end of tubing and inject it into the rock. It has been suggested that water would tend to enter the rock at certain spots, plugging the pores against steam flow. This could happen, however, whether or not a little water is run down the bore: the wet steam contains much more water, which will tend to separate out on the wall of the steam tubing. To help mix the water with the steam, baffles could be used near the bottom of the tubing. To further assure fine dispersion of the cooling water and good mixing, a constriction (nozzle of stainless steel) could be provided in the bottom length of tubing, with small holes through the tubing at that point and a packer set below it to close the annulus. The water would then spray into the high-velocity steam at the constriction and be atomized and well-mixed with the steam. Another suggestion is to install a packer part-way along the injection section, and inject the water at the top of the formation and the steam at the bottom (Ref. 11-5). This could help counteract steam override in the reservoir. These last two methods have the disadvantage of requiring a packing that withstands the steam.

(4) If cooling water is run down the annulus, some type of control system (preferably passive) may be needed to balance steam and water pressures at the well bottom. An orifice near the bottom may be helpful.

2. Development Sequence

Some analysis and preferable some laboratory work need to be carried out to resolve the points just mentioned. After that, a system of the kind outlined could be designed, fabricated, and installed for a field test.

I. AEROSPACE CONTRIBUTION

The aerospace contribution includes familiarity with heat flow associated with fluid flow with design for severe environments, and with high performance insulation methods and materials. It specifically includes familiarity with the use of fluid cooling to reduce operating temperatures and at the same time recover heat that would otherwise be lost (liquid-cooled rocket nozzles).

J. FINDINGS

It appears that heat losses and thermal stresses in steam injection wells can be considerably reduced, and the quality of the steam at the well bottom considerably increased, by using double-walled tubing with high performance insulation sealed between the walls. The two walls would be sealed together by welding near the ends of each length of tubing. This insulated tubing would be prefabricated and delivered to the field ready to run. Standard couplings would be used, on the inner-wall tubing only, and the tubing would be run in the usual way.

An additional small reduction in heat loss could be obtained by running a small percentage of the feed water down the annulus, instead of the steam generator.

Substantial cost savings should result especially for the deeper wells. This should make it possible to extend the depth at which recovery of heavy oil by steam injection is economically feasible and so increase petroleum resources significantly.

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SECTION 12

WATER SUPPLY FOR INJECTION

Concept: To upgrade water for generation of injection steam or for micellar flooding, the method used should be chosen to fit local conditions. Approaches considered should include multiple and hybrid systems using hollow fiber reverse osmosis and distillation, as well as distillation techniques utilizing a solvent-enhanced azeotropic boiling mixture, solar heat as an energy source, solar ponds for concentration separation, blending, and use of surfactants.

A. PROBLEMS ADDRESSED

Steam injection is a poven method of enhancing oil recovery, especially for very heavy crudes. Large quantities of water are needed to make the steam. Available water supplies are often brackish or limited in quantity.

For enhanced recovery by micellar and surfactant flooding, high salinity in the water used, and in particular high concentrations of divalent ions such as Ca^{++} and Mg^{++}, are incompatible with surfactants generally used (petroleum sulfonates). The surfactant is lost by precipitation and the precipitates themselves clog the formation.

Large quantities of water with high salt and sulfur content are often produced during petroleum recovery, and must be disposed of. The law provides for an evaluation of the potential impact of discharging such water into surface waters from point sources. The National Pollutant Discharge Elimination System requires use of the "best available technology economically achievable by 1983." At present, there is no economical method of desalting high concentration brines.

It is sometimes possible to reuse produced water for water flooding. To reuse it for steam injection or micellar flooding is rarely possible, unless the concentrations of salts, and sometimes of sulfur, are reduced by appropriate treatment.

There are many ways to produce fresh (or fresher) water from saline sources. However, to do it economically and with energy conservation is extremely difficult. Several major factors influence the cost of removing salt from waters: (1) The size of the facility, (2) The cost of energy and (3) The concentration of salt in the water. Each of these factors contributes to the overall cost structure that can push the price of water as high as several dollars per thousand gallons.

Sodium chloride concentration also has a pronounced effect on the removal of other components from the water stream, i.e., the divalent ions and heavy metal ions. High salt (or high electrolyte) concentration

can contribute to the failure of such processes as ion exchange, reverse osmosis, and electrical methods. Materials of construction also become a problem where high salt concentrations and temperatures are experienced.

B. POTENTIAL METHODS

Water treatment and conditioning for use in petroleum production can be accomplished in many ways providing it is economically expedient to do so. In some cases of very high dissolved solids, it may be more practical to bring in fresh water than to try to treat the produced or available water. A list of the more practical processes for desalination is as follows:

1. Distillation (High Salt Concentration Range)

   (1) Flash, film, submerged, using waste heat or solar.

   (2) Multiple effect vaporation (maximum fuel economy).

   (3) Solar stills, solar ponds (temperature gradient).

   (4) Vapor compression.

   (5) Foam separation.

2. Crystallization (High to Moderate Concentration Range)

   (1) Vacuum evaporation.

   (2) Vacuum freezing and vapor compression.

   (3) Hydrate formation.

3. Membrane (Moderate to Low Concentration Range)

   (1) Electrodialysis.

   (2) Transport depletion.

   (3) Reverse osmosis, including piezodialysis.

   (4) Ion-exchange.

4. Chemical (Moderate to Low Concentration Range)

   (1) Ion-exchange.

These processes vary widely in costs and rates of conversion. Major cost considerations are the capital investment, the cost and availability of energy and the operational costs. Rates of conversion includes the applicability of a given system to perform the required function, which is heavily dependent on the initial concentrations and the expected degree of purification. For instance, distillation,

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evaporation or crystallization are the only practical methods that can be used on high salt content waters. Waters containing less salt (brackish) can be economically desalinated with membrane processes (reverse osmosis).

It is essential that a quantitative level be put on the degree of purification that is required for a particular job. Water to be prepared for surfactant flooding and/or steam generation will usually need a higher level of treatment than water to be reinjected or discharged.

No general solution will be applicable to all cases experienced in the field. The treatment must be tailored to the particular circumstances. It is entirely possible that a single approach to the problem cannot be used. In that case a multiple or hybrid type system should be considered to produce the minimum quality water that can be tolerated. Salt concentractions in excess of 30,000 ppm can only be treated by some form of vaporization or distillation process. If salinity is less than 30,000 ppm, reverse osmosis may be practical. Capital investment for reverse osmosis is low compared to the cost of evaporation equipment. However, as the salt concentration increases the costs and energy requirements for reverse osmosis increase and the transfer rates decrease.

1. Reverse Osmosis

An interesting approach to membrane technology for reverse osmosis is the fabrication of the materials into hollow fibers. Some of these fibers and their corresponding systems have reached the marketing stage, such as DuPont's "Permasep" and others produced by Dow and Amicon. A new fiber recently announced by DuPont is claimed to have a 6-fold increase in performance rate with increased stability. Hollow fibers have two main advantages over conventional or spiral membranes: (1) They are self supporting which reduces the complexity (and costs) of the containment equipment and (2) They have a very high surface area to volume ratio which increases the capacity.

Another recent development in reverse osmosis is piezodialysis, in which a membrane with both anion and cation sites is used to speed osmosis; an increase of up to 8 times is claimed.

Reverse osmosis is not, however, a panacea; the membranes only function in a fairly narrow pH range and are very susceptible to fouling by suspended materials. This may mean that additional pretreatment is required, with an attendent increase in capital and operating costs. A very concentrated reject stream is produced by reverse osmosis, which may require additional treatment before discharge.

2. Distillation

Among the newer approaches to distillation methods is the use of a solvent as the transport medium for salt-free water. Figure 12-1 illustrates this approach.

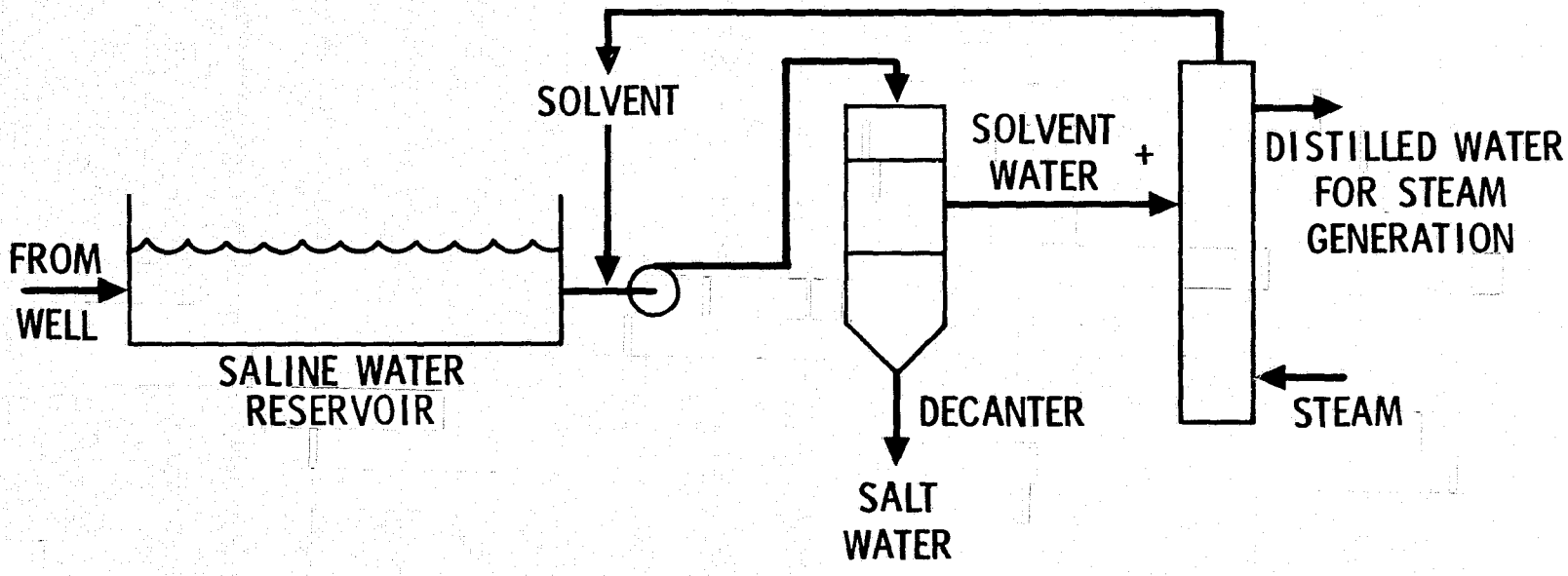

Figure 12-1. Solvent-Enhanced Distillation of Saline Water

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Another concept is to use solar heat for distillation. Many implementations have been studied; in general they do not appear economic at present prices. One interesting concept is the combination of a solar still with a solar pond (Figure 12-2). Free convection in the unstirred pond moves the hotter water to the top and the more saline water to the bottom; both effects increase the rate of evaporation and so lower costs.

Blending of water from various sources or processes may produce satisfactory water at lower cost than any single source.

A new patented distillation process that adds a surfactant and uses a two phase, foamy, liquid-vapor in a vertical tube evaporator may be useful for high brine waters (Ref. 12-1). This process is claimed to double heat transfer performance and cut costs.

C. DEVELOPMENT NEEDED

The following initial studies appear appropriate:

(1) A study to obtain information on the cut-off concentrations of the various existing processes. This should also include the examination of the practicability of multiple and hybrid systems using hollow fiber reverse osmosis technology and evaporation (distillation).

(2) A new type of distillation system using a solvent as the transport medium for salt-free water.

(3) Solar stills utilizing solar ponds for establishing a concentration gradient in the salt water, to improve efficiency and lower costs.

(4) Various approaches such as blending treated water and the use of polyelectrolytes and surfactants in the boiler feed water to reduce processing energy requirements.

D. AEROSPACE CONTRIBUTION

The aerospace contribution includes background in solar energy, thermal insulation, thin films, instrumentation, and new seimpermeable membranes.

E. FINDINGS

A variety of methods are available to purify available water to meet the requirements of steam injection and micellar flooding, and to purify produced water for disposal or reuse. The choice of method depends on the composition of the available water, the composition required for utilization or disposal, the size of the plant, and the costs of energy

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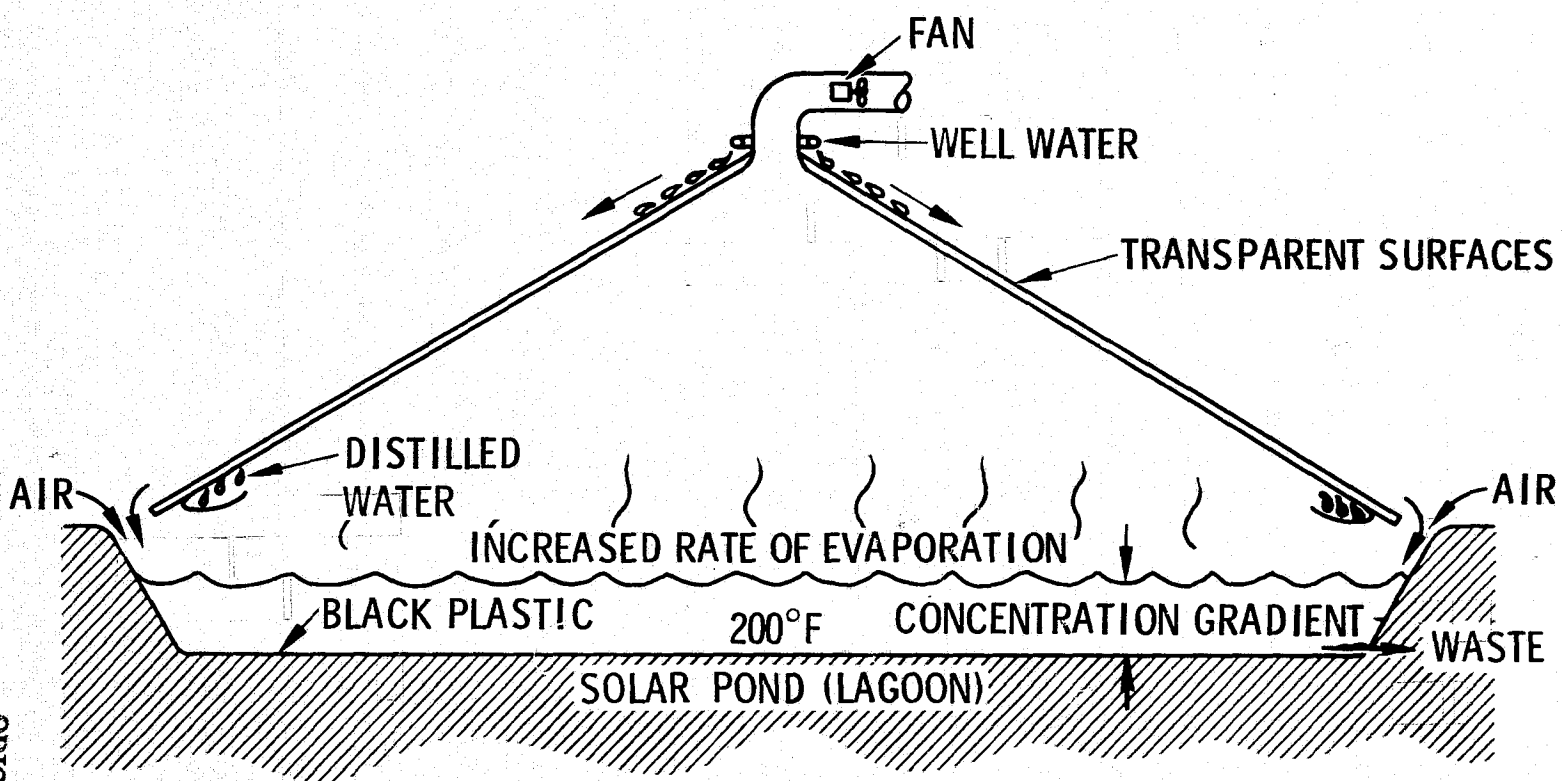

Figure 12-2. Solar Still With Solar Pond: A Concept (Free convection in unstirred solar pond moves warmer water to top and more saline water to bottom. Both effects increase rate of evaporation.)

and capital. A combination of methods may sometimes be the best choice.

A study to obtain information on the cut-off concentrations of the various existing processes, singly and in combination, appears worthwhile. Studies also seem appropriate on systems using hollow-fiber reverse osmosis technology in combination with distillation, and on distillation systems which use a solvent-enhanced azeotropic boiling mixture, solar ponds with concentration separation to reduce costs, blending, and surfactants in the feed water.

SECTION 13

NON-POLLUTING HEAT TO GENERATE INJECTION STEAM

Concepts: A) Burn crude oil in 2 stages. Remove sulfur as H_2S between stages. B) Desulfurize crude with chlorine. C) Use solar heat. This does not appear economical.

A. PROBLEM ADDRESSED

Steam injection is a proven technique for enhanced recovery, especially of heavy crudes. Availability of non-polluting heat for steam generation is, however, a serious problem. Use of natural gas to raise steam is ceasing to be practical. Crude from the field is widely used, but these crudes typically contain more than 1% sulfur, and emission of sulfur dioxide is severely limited by air pollution regulations. Scrubbing of SO_2 from the stack gas is possible but expensive. Sulfur can be removed from the oil at a refinery, but this adds major refining and transport costs.

Other products of combustion can also present pollution problems. Emission of nitrogen oxides (NO_x) is strictly regulated in California; even an increase in CO_2 production is forbidden. If enforced, this would prevent increased use of any fuel, unless a corresponding decrease in use elsewhere in the area is arranged.

B. METHODS

Three methods of reducing pollution were considered: 2-stage combustion, desulfurization by chlorinolysis, and use of solar heat. These will be described in turn.

C. TWO-STAGE COMBUSTION METHOD

This method based on carrying out the combustion in two stages. The fuel is essentially gasified in the first stage by burning under rich conditions, i.e., with insufficient air. The sulfur in the fuel is then released as hydrogen sulphide, which can be removed by absorption on zinc oxide or iron oxide or lime. The resulting clean gas can then be burned with more air to produce water and carbon dioxide as clean combustion products (Fig. 13-1).

The two-stage combustion process has another advantage in that it essentially eliminates NO_x production. The heat of combustion is released in two fractions, with cooling to the steam tubes, so that the flame temperature does not exceed the minimum NO_x formation temperature of 2700°F.

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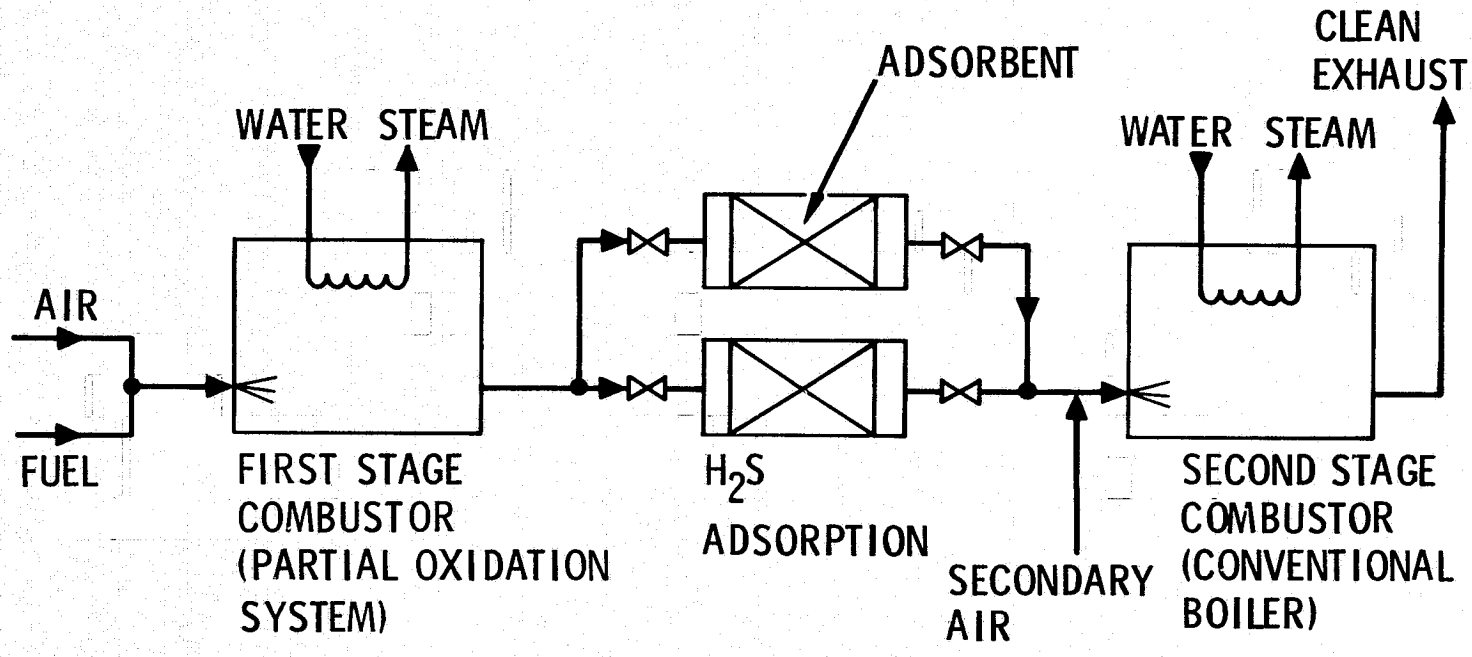


Figure 13-1. Two-Stage Combustion of Crude Oil With Hydrogen Sulphide Removal Between Stages

1. Advantages

(1) As compared to removal of sulfur dioxide from flue gas, 2-stage combustion reduces the volume of gas handled. This should reduce costs significantly.

(2) Produces less NO_x, an important pollutant.

(3) H_2S is less corrosive than SO_2, so corrosion problems with the scrubbing equipment should be less.

2. Disadvantages

(1) Less development work has been done, as compared to stack scrubbing of SO_2.

3. Development Needed

The minimum air to fuel ratio required to gasify the crude oil without producing soot is not known and must be determined. Work at JPL on gasification of gasoline has shown a minimum air to fuel ratio of 8 (by weight) is needed. A range of 10 to 11 may be required to obtain soot-free combustion with crude oil.

Another problem is to find the most economical way for removing the hydrogen sulphide. As indicated above, various metal oxides can be used. Whether this should be a regenerable process or not needs also to be defined. The use of zinc oxide is well established but may be somewhat expensive with high sulfur crudes.

An economic analysis must be carried out for the various alternatives.

After these steps have been taken, the overall feasibility could be demonstrated with a pilot plant.

4. Aerospace Contribution

The aerospace contribution includes expertise in the chemical aspects of combustion originating from work on rocket propulsion and involving considerable experience in utility power plant combustion.

D. DESULFURIZATION BY CHLORINOLYSIS

To meet EPA emission requirements of 0.8 lb SO_2 per million BTU and to eliminate or minimize the need for expensive flue gas treatment, the sulfur content in the crude has to be reduced to approximately 0.2 percent. Hydrodesulfurization of crude oil, with cobalt-molybdenum or nickel-molybdenum catalysts on alumina support, is the refinery process in current use. The requirements of catalysts, hydrogen consumption and severe reactor operating conditions make the hydrodesulfurization process quite expensive.

1. Method

The proposed concept for oil desulfurization consists of:

(1) Chlorination of the oil, mixed with a suitable amount of water.

(2) Dechlorination of the oil by chemical or thermal treatment.

(3) Dewatering.

2. Background

Sulfur is present in the crude oil primarily as organic sulfur, and mostly in the form of thiophenic compounds (Table 13-1). Both the carbon-sulfur and sulfur-sulfur bonds have to be broken for successful desulfurization.

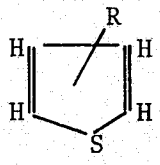
The "Coal Desulfurization by Chlorinolysis" process, developed at JPL, has demonstrated that chlorine, in the presence of water, removes both the pyritic and organic sulfur from coal. This chlorinolysis process has shown very promising technical feasibility for coal desulfurization and is under active development with sponsorship, in turn, by N.A.S.A., the Bureau of Mines, and the Department of Energy. Since the sulfur in oil is similar to the organic sulfur in coal, it is reasonable to expect that a modified chlorinolysis process will be applicable for oil desulfurization.

3. Laboratory Experiments

JPL has conducted preliminary laboratory tests of a version of the proposed concept, using a Bakersfield, California crude containing about 1% sulfur. Three chlorinating agents, viz, chlorine (gas, acidic), NaOCl (4-6% liquid, alkaline, pH = 11), and $Ca(OCl)_2$ (solid, approximately neutral) were tried in the chlorinating step. Dechlorination at 260°C, hydrolysis at 100°C in an extraction apparatus, filtration and distillation were conducted after chlorination to obtain the desulfurized oil. The product was analyzed for residual chlorine and sulfur contents. The results, particularly the sulfur removal achieved, suggested that the concept of using a chlorine oxidative process to remove organic sulfur from crude oil is workable. The particular procedure and conditions adopted did not provide sufficient sulfur removal for this oil. Also, utilization of expensive $Ca(OCl)_2$ is not economically practical.

A different procedure was therefore tried. A high sulfur Arabian crude (2.37% sulfur by weight) was used. Chlorine gas was introduced into stirred vessel containing the crude and a small amount of water, at room temperature and ambient pressure. The mixture was then washed, heated with steam, and rewashed.

Table 13-1. Sulfur Compounds Found in Crudes

COMMON NAME	FORMULA	SCIENTIFIC NAME
Sulfur	S	
Hydrogen sulfide	H_2S	
Mercaptans	R-SH	-Thiols
Sulfides I or alkyl sulfides	R-S-R'	Thia-(alkyl radicals)
Sulfides II or cyclo sulfides (include aryl sulfides)	R-S-R'	Thia-cyclo-(alkly..)
Disulfides (and poly-sulfides)	R-S-S-R	(Dithia-(alkly..)
Thiophens (and derivatives, include condensed thiophens)		Thiophen and thiophen derivatives

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Rationale for this procedure was as follows: At low temperature, chlorine tends to selectively attack the sulfur atoms in the oil structure to form sulfenyl compounds, which are further oxidized to sulfates or sulfuric acid in the presence of water. The sulfates and sulfuric acid can be easily leached out by a simple washing step. The desulfurized petroleum hydrocarbons can be dechlorinated by heating with the help of steam. In the dechlorination step, the peripheral chlorine atoms in the hydrocarbon matrix will be hydrolyzed by another water washing stage to leach out the by-product HCl.

In the first test of this procedure, sulfur removal efficiency was 81%, leaving a residual sulfur of 0.46%. The residual chlorine was too high, 7.91%. The primary purpose of this run was to test the extent of sulfur removal under an excessive chlorine flow rate for a long time. The residual chlorine content, the sulfur removal capability and the processing time are expected to improve under an optimum condition.

The results of these preliminary experiments support the proposed concept of oil desulfurization and suggest the need for a systematic parametric study to determine the technical feasibility of a practical process. The dechlorination step, in particular, has to be examined thoroughly so that the residual chlorine can be brought down to acceptable levels. A potential improvement method in the dechlorination step is to add caustic limestone solution or dolomite to help remove the chlorine compounds at low temperature.

4. Advantages

(1) The engineering operations involved are very simple and could easily be implemented in the oil field.

(2) Potential low cost compared to catalytic hydrodesulfurization since such high temperatures are not required and the method is so simple.

(3) Potentially high efficiency in sulfur removal.

5. Disadvantages

(1) Need for disposing of chlorine-containing waste.

(2) Development needed, including methods of reducing residual chlorine in the oil.

6. Development Needed

Initially, investigation is needed to:

(1) Study the technical feasibility of a modified chlorinolysis process for oil desulfurization.

(2) Optimize the chlorinolysis process for best oil desulfurization results.

(3) Study chemistry and kinetics of the various steps in the oil chlorinolysis process.

(4) Study the economic feasibility of the chlorinolysis process for application to crude oils, specifically for steam generation in thermal recovery of oil and power generation.

This could be done as 3 tasks:

Task 1. Parametric study of the chlorination, dechlorination and hydrolysis steps. A high-sulfur (1-3%) crude oil sample will be used for the parametric studies. For the chlorinolysis step, the effects of moisture content, temperature, time of chlorination and the chlorinating agent will be evaluated. For the dechlorination step, in which hydrolysis and removal of water solube sulfates takes place, the effects of temperature, duration, water to oil ratio will be studied.

The results of these parametric studies would determine the optimum chlorinolysis process.

Task 2. Study of the chemistry and kinetics of the chlorinolysis process. Theoretical and experimental studies will be conducted to elucidate the reaction mechanisms and kinetics of the chlorination, dechlorination and hydrolysis steps. This will enable modeling, optimization and control of the desulfurization by chlorinolysis process.

Task 3. Economic evaluation of the oil desulfurization by chlorinolysis process. A chemical engineering economic analysis of the proposed process will be made. The costs of this process will be compared to existing oil desulfurization processes, particularly the hydrodesulfurization and flue gas treatment processes. A combination process--partial desulfurization by chlorinolysis together with flue gas scrubbing--will also be analyzed.

7. Aerospace Contribution

The aerospace contribution includes considerable knowledge of sulfur binding in organic materials, arising out of extensive work on polymers for use in solid propellants. Also, NASA-supported work has been underway for the past 3 years on coal desulfurization by low temperature chlorinolysis and other chemical techniques. Thus laboratory and bench-scale work on a variety of coals is now being extended to engineering-scale chlorinolysis.

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E. USE OF SOLAR HEAT

1. Method

Solar heat is suggested as a replacement for all or part of the fuel used for generation of injection steam. Three variations have been considered:

(1) Full solar replacement of oil-fired steam generators. This includes storage for 24-hour operations.

(2) Daylight-only replacement of fuel-oil usage.

(3) Partial solar use, for feedwater heating.

For steam generation, the proposed solar collectors are parabolic troughs, with a linear receiver at the focus, these track the sun. For feedwater heating, a combination of parabolic troughs with non-tracking flat-plate collectors is proposed, and appears to be the most economical design.

2. Qauntitative Characteristics

The 3 variations are analyzed in some detail in Appendix H, taking as an example conditions in the Bakersfield area. Emphasis is on economic aspects.

3. Economic Evaluation

In the example considered, replacement of fuel (R-crude at $12/bbl) by solar heat would increase the overall cost of steam generation by a factor of 3 to 4, even with many assumptions favorable to solar. For feedwater heating, the cost ratio is also unfavorable. Even escalating fuel costs do not make a reasonable pay-back period seem likely.

4. Advantages

(1) Avoidance of pollution problems.

(2) Saving of oil or other fuel.

5. Disadvantages

Costly; more costly than fuel fired system and requiring much greater capital investment.

6. Development Needed

If a decision were made to proceed with such a plant, design could commence on the basis of the knowledge now available.

7. Aerospace Contribution

The aerospace contribution includes extensive background in the utilization of solar energy, both for electricity and heating, including work activity in progress on steam generation by solar heat on a semi-commercial scale.

F. FINDINGS

For generators of injection steam which are fired by crude oil, both 2-stage combustion and desulfurization of the crude by chlorinolysis give promise of meeting sulfur emission standards, perhaps at lower cost than conventional stack scrubbing.

In 2-stage combustion, the crude would be burned with limited air to produce heat and gas. H_2S would be scrubbed from this gas, which would then be burned with more air to produce more heat. Advantages as compared to conventional combustion and scrubbing are that a considerably lower volume of gas is handled in the scrubber, the sulfur is scrubbed out as H_2S rather than as the more corrosive SO_2, and the combustion is at lower temperature, so less NO_x pollutant is emitted.

The crude-desulfurization approach contemplates chlorination of the crude at room temperature and ambient pressure, followed by dechlorination with steam and washing. It promises a method much simpler to carry out in an oil field than catalytic hydrodesulfurization.

Both of these methods would need development work and economic evaluation. In the chlorinolysis technique, removing the chlorine from the crude would need special attention.

Examination of the possibility of using solar heat for generation of injection steam or for preheating generator feed water indicates that it is not economic, and is not likely to become economic in the near future.

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SECTION 14

SEALS AND FLEXIBLE COMPONENTS FOR DOWNHOLE USE

Concept: Development of elastomers with improved high temperature properties by: (a) Increasing the strength of polymers that are soft at high temperatures through cross-linking and through reinforcement with glass fibers; and (b) Increasing the flexibility of polymers, such as poly (phenyl quinoxaline), that are rigid at high temperatures through incorporation of flexible units into their molecular structure.

A. PROBLEMS ADDRESSED

Many downhole devices - logging tools, cables, packings, downhole drill motors, etc. - utilize rubber and other elastomers in such components as seals, sleeves, electrical insulation, flexible elements, and so forth. At temperatures above 200°F (100°C), these components often fail or have short life.

B. WORK COVERED

An effort is under way at JPL on development and evaluation of elastomeric materials for geothermal applications. The work is sponsored by the U.S. Department of Energy and does not form part of the NASA-sponsored, petroleum-oriented, study on which this publication is based. It is reported briefly here, for completeness.

C. TECHNICAL EFFORT

The goal of the 3-year D.O.E. effort is to develop improved elastomeric materials to withstand the severe environments of geothermal resources. The first year's objective will be to develop an elastomer from commercial materials that will perform satisfactorily for 24 hours at 260°C (500°F) and at a pressure differential of 1500 psi (10^7 N/M^2) for packer applications in a geothermal environment. A longer term objective is to synthesize new polymer systems for geothermal applications at higher temperatures and pressures.

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The approach incorporates a survey of existing commercial materials, including an assessment of environmental capabilities determined by the drilling industry and others, to arrive at an evaluation of the most promising of these types of materials for geothermal applications. If any appear to be likely candidates for improved materials, they will be formulated and tested. A concurrent task will be to evaluate materials which may not yet be commercially available, but for which synthesis procedures have been established. A third task will involve synthesizing and evaluating materials that appear from estimates of

property-structure relationships to be promising candidates, but for which detailed synthesis procedures have not been developed.

Some novel features have been devised in the detailed approach. Since it was known that even relatively stable elastomers such as Vitons lose most of their mechanical properties (reversibly) at higher temperatures, it was believed necessary to formulate these elastomers to obtain the best properties possible at high temperatures, even though hardness and modulus would be very high at room temperature. Furthermore, in the synthesis work, the approach has been to attempt to prepare stable high temperature elastomers on the basis of synthesis procedures developed for rigid high temperature polymers, such as poly(phenyl quinoxalines). Such elastomers would be expected to be elastomeric at use temperatures, but rigid at room or even considerably higher temperature.

1. Testing

It has been found that even the most stable commercially available elastomers are marginal for use at 260°C (because of the reversible decrease in properties mentioned above). DuPont Kalrez, a copolymer of perfluoromethylvinyl ether and tetrafluoroethylene and AFLAS 150H, a copolymer of propylene and tetrafluoroethylene produced by the Asahi Glass Co. in Japan have been found to be sufficiently thermally stable at 260°C (500°F), but in formulations tested so far, tensile strengths measured at the same temperature are only 200 to 300 psi (1.4 to 2.1 x 10^6 Pascal. Viton formulations have been prepared and tested, but are less thermally stable than Kalrez or AFLAS (Figure 14-1). The cost of Kalrez is too high (more than $4000/kg) for many important applications, such as packers. The availability and cost of AFLAS 150H are being determined. It appears that there is no way to relate measured mechanical properties to performance, especially if the properties are relatively marginal. Therefore, the best formulation developed will be tested as a casing packer in a downhole geothermal environment.

2. Formulation

Several formulation methods are being tried to improve high temperature performance of available polymers. With polystyrene, cross-linking is being attempted. With proplylene-tetrafluoroethylene copolymer (AFLAS), new formulations are under investigation. With Viton, work is in progress on reinforcement with glass fibers. A saline coupling agent was applied to the glass. With 5% glass fibers, the strength at 260°C was increased 50%. However, aging performance was poor; it was found that the glass fibers lose 7% of their weight in 40 hr at 260°C in water.

3. Synthesis

With respect to synthesis of new materials, the survey has indicated that no new synthesis procedures have been developed that could be used for the preparation of promising candidate materials.

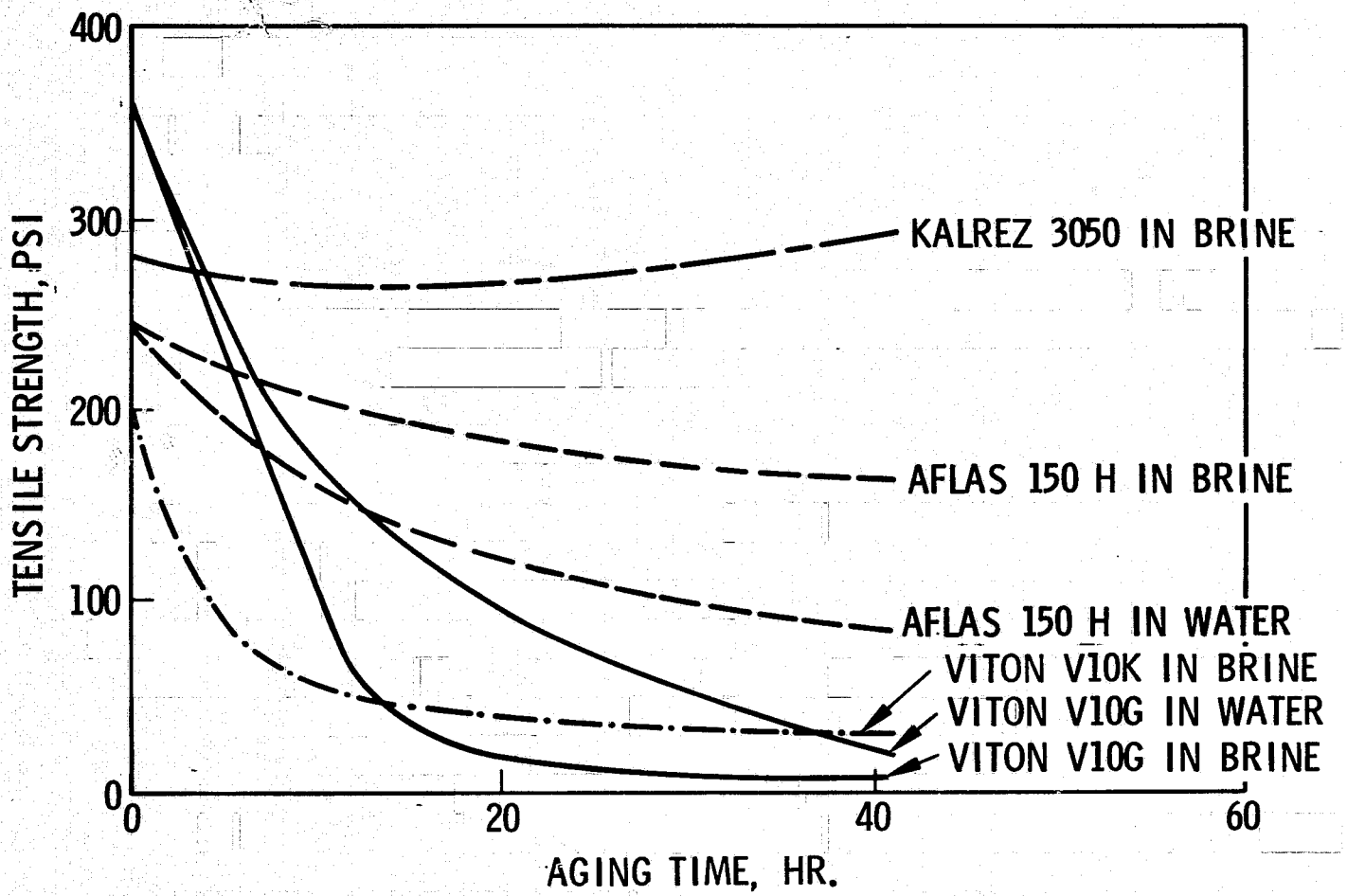

Figure 14-1. Effect of Aging Elastomer Compositions in Deionized Water and in Brine (Aging and tensile testing at 260°C (500°F).)

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Therefore, procedures are being developed for the preparation of new elastomers. Two types of polymer systems are being investigated. One consists of poly(phenylquinoxaline) segments with more flexible units attached to make the polymer elastomeric at high temperatures. This type of polymer will probably have to be crosslinked by radiation or chemical methods to prevent plastic flow at use temperatures.

The second type of polymer to be synthesized and evaluated will also consist of rigid segments with a second order transition temperature higher than the use temperature, with longer flexible chains between the rigid segments. (These are known as block copolymers and are commercially available for lower temperature applications). The hard blocks or rigid segments function as crosslinks and the soft blocks (flexible chains) carry the load elastically. Here too, poly(phenyquinoxaline)s, which are stable at 575°F (300°C) or higher, are being tried for the hard block; the stability of available soft block polymers may be inadequate. The synthesis scheme and some results are shown in Figures 14-2 to 14-5.

D. FUTURE WORK

Plans on the D.O.E. development work include:

(1) Modelling the coupling reaction

(2) Coupling hydroxy terminated polyquinoxaline with brominated polybutene

(3) Formulation of Viton and AFLAS gums with treated asbestos fibers

(4) Crosslinking and formulation of polystyrene

(5) Immediate goal of 500 psi tensile strength and 50% elongation at 260°C (500°F), with good aging behavior.

E. AEROSPACE CONTRIBUTION

This effort utilizes extensive experience in the synthesis of polymers and development of elastomers for solid propellant rocket fuel.

F. FINDINGS

Work on synthesis of new polymers and on new formulations is under way, aimed at development of elastomeric materials for downhole use in geothermal wells. This effort is based on aerospace experience.

The knowledge gained should be useful in developing elastomeric

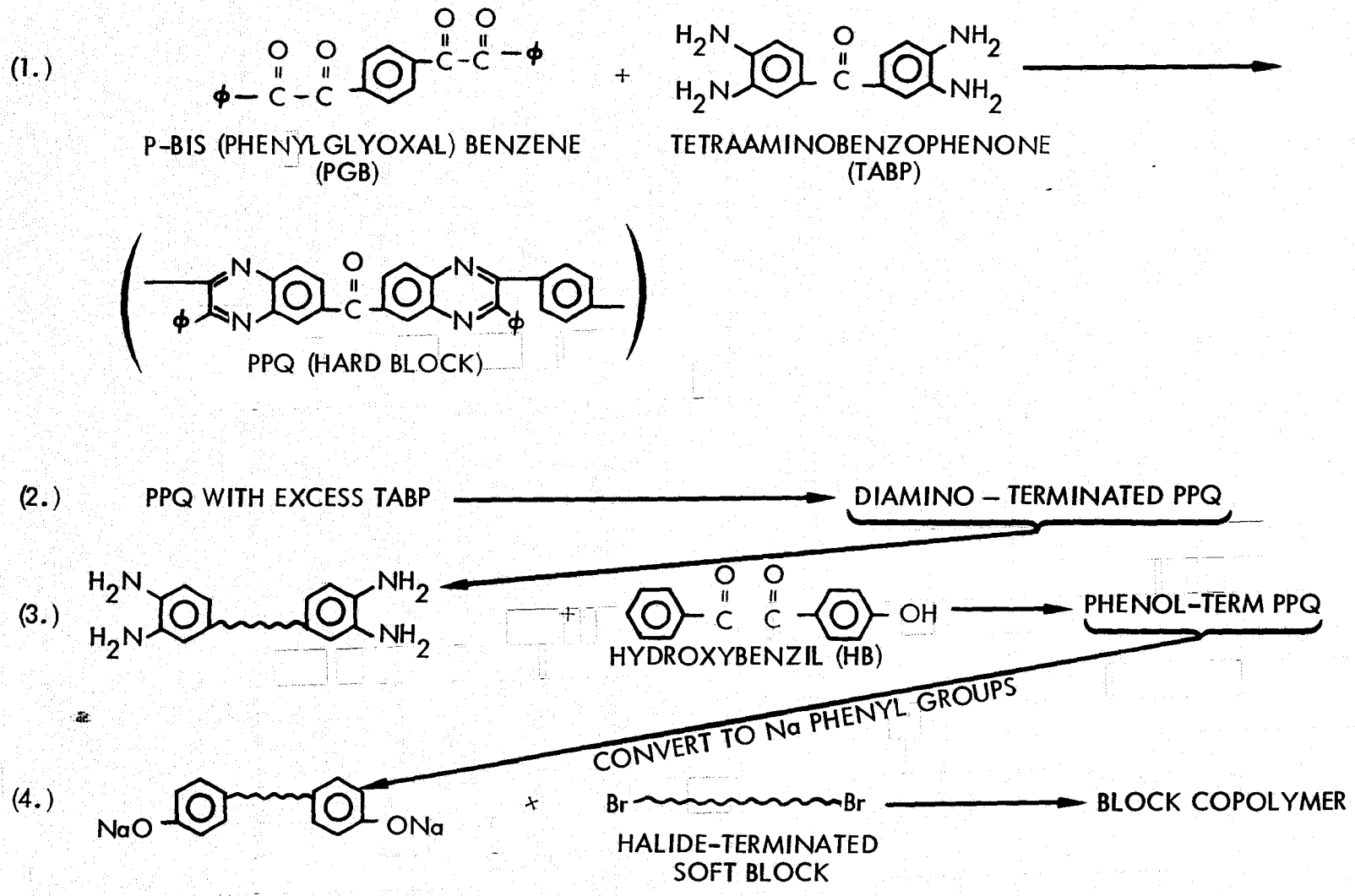

Figure 14-2. Synthesis Scheme - Polyphenylquinoxaline (PPQ) Block Polymers

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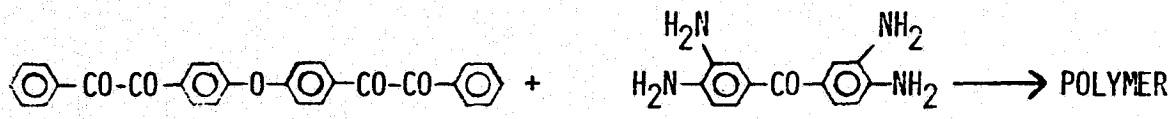

ODB TABP

POLYMER NO.	% EXCESS TABP	M_W (GPC)	M_N (VPO)	CALC. M.W.	REMARKS
1	0	-		-	POWDERY
3	2	-		-	BENDABLE FILM
4	2.7	30,000	8,500	-	TOUGH, CREASIBLE FILM, T_G 265°C
11	2.7	22,500		-	SCALEUP OF 4
7	5	-		-	HARD, STICKY FILM
5	7.6	-		-	BRITTLE FILM
101	14	9,000	3,009	5,000	BRITTLE FILM, COLORIMETER END GROUP ANALYSIS 0.02, -0.05 wt % NH_2.
101R	14	-	2,140	5,000	"
102	10	-	2,956	7,000	"

Figure 14-3. Synthesis - Hard Block Preparation

POLYMER	X (END GROUP)	YIELD, %	END GROUP ANALYSIS, % OF THEORETICAL
POLYGLYCOL ETHER (1)	CHLORIDE	50	65
POLYGLYCOL ETHER (1)	TOSYLATE	40	LOW
TELAGEN S (2)	CHLORIDE	80 - 90	78
TELAGEN S (2)	TOSYLATE	~90	UNREACTIVE (?)

(1) M.W. 1500

(2) M.W. 1980,
FUNCTIONALITY 1.84

Figure 14-4. Synthesis - Soft Block Preparation
X ~ Polymer ~ X

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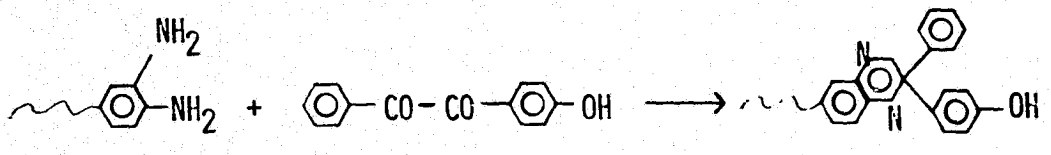

POLYMER	M.W.	% EXCESS HB	EQUIV. WT/PHENOLIC OH
101	3009 2140	10	~2500

COUPLING REACTION

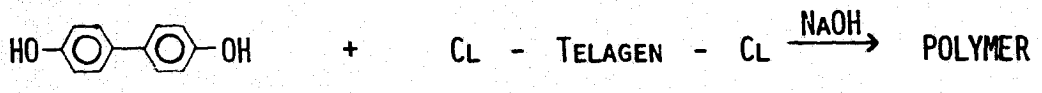

Figure 14-5. Synthesis - End Capping Reaction

materials for service in petroleum wells. However, the materials developed for geothermal service may not be directly applicable for petroleum, since resistence to degradation by hot hydrocarbons is not prescribed.

SECTION 15

LONG-LIFE DOWNHOLE DRILL MOTOR

A. PROBLEMS ADDRESSED

Applying the drill bit rotation power at the bottom of the hole by means of a motor operated by drilling mud or electrically has been attempted for many years, since there are several advantages to this method over the conventional rotary system. The conventional rotary drilling system utilizes a drill bit rotation by a string of pipe leading to the surface. This pipe transmits the rotation force from the rotary table, which is located at the surface and is powered by the drilling rig, to the drill bit at the bottom of the hole. Although this method has been used successfully to drill hundreds of thousands of holes, there are several special conditions where the equipment is inefficient. Rotation of long lengths of drill pipe results in pipe wear, extreme metal fatigue leading to failure of the pipe, friction between the pipe and hole which reduces available power at the bottom of the hole, and difficulties in drilling deviated holes accurately. The downhole motor eliminates these problems since there is no need to rotate a long string of pipe. The drill motor provides the torque while the pipe remains stationary, acting as a conductor for the drill mud or electrical power, a method of suspending the drill motor and bit in the hole, and a way of providing force to react against the torque developed by the drill bit as it rotates against the rocks being drilled.

Downhole motors presently are used in the Soviet Union, where about 70% of the wells are drilled with a mud-powered turbodrill. The Soviet designed turbodrill was licensed to a U.S. company but has not been successful here because of low torque, high speed and limited seal and bearing life. The seals limit drill bit pressure drop to 100 to 300 psi, which is inadequate for removal of hole bottom cuttings. The bearings are lubricated by the abrasive drill mud which damages the bearings. The operating speed of these motors are from 300 to 1000 rpm and conventional roller bit bearings cannot withstand this high speed. This generally requires the use of expensive diamond bits. Finally, a turbodrill can stall under overload conditions and no immediate indication is available at the surface. Only after a period of time is the condition noted by lack of drilling penetration.

In the United States almost all wells are drilled with conventional rotary drilling techniques, with downhole motors used almost exclusively for directional drilling. A large portion of these deviated holes utilize a positive displacement Moineau type mud motor for drilling only the changes in direction of the hole. This motor utilizes an eccentric steel rotor in a shaped rubber stator to produce torque. Once the desired direction is established, conventional drilling is again used for the remainder of the hole. This is because of the expense of using the short life, higher speed mud motor. The Moineau type motor also suffers bearing life problems as well as wear and failure of the rubber stator especially at high temperatures. The

rotational speed is in the range of 300 to 500 rpm, somewhat less than a turbodrill. Both standard rollercone bits and diamond bits are used. If the motor stalls, an immediate increase in back pressure is noted thus informing the driller of a problem. USA experience has shown that at present the Moineau-type drill motor has been more economical to operate than the turbodrill for the drilling situations encountered.

Thus, though downhole drill motors promise reduced drilling cost, which would be significant both in developing new fields and in enhanced recovery projects, the motors that have been available so far have not had adequate life or low enough maintenance cost to make them competitive with conventional drilling.

B. STUDY APPROACH

During Phase 1 review of this study it was recommended that a preliminary effort be made to determine what work is underway on development of improved downhole drill motors under ERDA, aerospace, or other sponsorship as well as what is known of Soviet equipment. Deficiencies in existing and proposed equipment would be identified and concepts sought for overcoming the deficiencies.

The study approach was to first conduct a literature survey to assess the current state-of-the-art and to identify the underlying problems that have impeded the development or introduction of new technologies into the development and improvement of downhole motors. Next, discussions were held with equipment manufacturers and organizations active in research and development on drill motors to gain further insight into the technological and nontechnological problem areas faced by the industry and to assess the probable match between industry's needs and aerospace technology.

C. DOWNHOLE MOTOR DEVELOPMENT PROJECTS

Several companies were reported to be working on downhole motors. The following list may not include all participants due to the time limitations of this study.

	Company/Agency	Type
(1)	Engineering Enterprises, Inc.	turbodrill
(2)	Maurer Engineering/DOE	turbodrill
(3)	Allegheney-Ludlum	geared vane
(4)	A-Z International	geared Moineau
(5)	Baker Oil Tool	multi-lobe Moineau
(6)	General Electric Co./DOE	geared electrodrill
(7)	Schlumberger	Moineau
(8)	Soviet Union	multi-lobe Moineau
(9)	Dynadrill	Moineau

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(1) Engineering Enterprises, Inc., Houston, Texas has been developing a mud powered, sealed lubricated bearing turbodrill. In the May 30, 1977 issue of the Oil and Gas Journal, it was reported that the new design had been operated for a 60 hour period at speeds of 1,400 rpm and bit weights up to 35,000 lbs. with drilling rates up to 100 ft/hr. A leak in the sealed lubrication system developed, terminating the test. Analysis of the leak will be performed and the cause determined. Continued testing is planned once the problem is corrected.

(2) Maurer Engineering Inc., Houston is working under subcontract to Terra Tek, Inc., Salt Lake City, to design improved drilling motor bearing assemblies and components which will be tested by Terra Tek. All work is sponsored by DOE with Terra Tek being the prime contractor. An additional goal is to develop improved seals that will operate at bit pressure drops in excess of 1000 psi for improved bottom hole cleaning. An integral part of the seal development will be selection of an optimum lubricant.

(3) Allegheney-Ludlum is working on a positive displacement flexible vane motor coupled to a gear reduction system so that present drill bits can be used at normal speeds (50 to 100 rpm).

(4) A-Z International is reported to be developing a geared Moineau type motor but no specific information is known.

(5) Baker Oil Tool is developing a multilobe rotor, multiple cavity stator Moineau type mud motor. Such a design would provide higher torque and lower speeds than single lobe types.

(6) General Electric Company is working under contract from DOE to test an electric powered downhole drill motor which was developed by GE and Cullen. The system combines the downhole motor with real-time data acquisition with surface display and command features. The motor power and data telemetry links between the surface and downhole are carried by a specially designed multi-conductor cable.

Two drill motors are to be demonstrated; a 60 HP motor designed for directional drilling and a 285 HP motor for use in deep, hard drilling situations. The data system currently includes direction parameters, temperatures and vibration data. Apparently other parameters such as bottom hole pressure, bit torque, speed and weight, and formation characteristics could be added to the sensing package which would contribute greatly to improved drilling efficiency and safety.

In addition to GE/Cullen, several industry participants include Amoco Production Co., Union Oil of California, Chevron Oil Field Research Co., Dresser Industries and Brown Oil Tools Co.

(7) Schlumberger is reported to be working on a Moineau type motor but nothing specific can be reported.

(8) The Soviet Union is reported to be developing a multi-lobe Moineau type motor. Evidently tests are being conducted with several designs using different number of lobes and the results of these tests are apparently encouraging. It is interesting to note that the Russians, who developed and used the turbodrill for many years, are now experimenting with positive displacement motors more in line with successful American devices.

(9) Dynadrill, which has been very successful in developing and using the Moineau concept, is apparently working on improved designs especially in the areas of better heat resistance and longer life bearings with sealed lubrication systems.

In the earlier study of applications of aerospace technology to petroleum exploration, it was noted that an aerospace organization, Rockwell International's Rocketdyne Division, had proposed a multi-stage hydraulic turbine as prime mover, together with a cylindrical clamshell system in which shell segments are locked against the wall by hydraulic cylinders (Ref. 1-1). Both drilling force and torque resistance are thus provided locally, rather than by the drill pipe. This concept has not been pursued, apparently because of funding limitations.

In the earlier study, several other non-conventional drilling concepts were reviewed, including: (1) automated drilling rig (2) improved high pressure drilling (3) resonant-vibration drilling, and (4) combustion-fracture drilling (Ref. 1-1). A brief survey of the present status of these concepts was conducted as part of this study. Some industry work has been done on automating certain portions of the drilling operations such as drill pipe handling. Apparently the high pressure drilling projects have been terminated by the sponsoring oil companies because of a number of unsolved or uneconomical problems. The resonant-vibration drilling concepts were being applied to coal mining applications but nothing more was being done in oil well drilling. There had been no further research on combustion-fracture drilling probably because it is a very advanced concept which would require many years of work to show feasibility.

D. AEROSPACE CONTRIBUTION

Potential aerospace contribution includes expertise in mechanical and electrical engineering, vibration analysis, fluid mechanics, stress analysis, materials, control, and systems engineering.

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E. FINDINGS

Several very competent companies are heavily involved in development of various downhole drill motor concepts.

The primary technical problems with downhole mud motors are abrasion of bearings and seals, excessive rotation speed, low torque, and lack of real-time surface data on drilling parameters. The primary technical problems with downhole electric motors are power transmission, life of seals and bearings, and short field experience.

Problems of materials, lubricants, and novel designs are being addressed and aerospace technology is probably an integral part of the projects since NASA technology transfer has been very complete with respect to these problems. Most of the industry people interviewed indicated that a good deal of aerospace technology has been assimilated into their hardware.

Under these circumstances, it appears that further contribution by aerospace technology is most likely to come in such areas as development of better elastomers, as described in the preceding section, and in helping individual companies solve particular problems associated with their individual, often proprietary, designs.

SECTION 16

MISCELLANEOUS PROBLEMS

A. CONCEPTS

There were a number of other petroleum extraction problems, identified in Phase 1 of this study, for which concepts based on aerospace technology were identified and appear worthy of further consideration. The resources available for this study did not allow such consideration. A few of the items were examined in the earlier study on exploration (Ref. 1-1).

These problems are listed below, together with the concepts intended to aid in their solution. Each problem is identified by its problem number in Appendix C, where the problems are discussed briefly in numerical order.

A1a. Reduction in Drilling Costs

Concepts: Improved downhole drill motors. Improved high pressure drilling. Automated drill rigs. Vibratory drilling. Combustion-fracture drilling. (See Section 15 and previous report Reference 1-1). Long-stroke screw-actuated mud pump.

E2e. Improved Logging Methods for Detection of Fractures

Concepts: Acoustic back-scatter log (Ref. 1-1). Downhole seismic tomography (See Section 7).

E2g. Measuring Stresses in Reservoir and Bounding Rocks

Concept: Cutting away material from borehole wall and measuring deformation (Ref. 16-1).

E3d. Transmission of Drilling and Logging Data to and from Central Computer.

Concepts: Error-correcting codes. Public service communicators satellite.

F2a. Improved Numerical Modeling of Reservoirs

Concepts: NASTRAN finite element method. Inversion using production data.

G1b. Stability of Polymer Solutions
G1d. Cost of Polymers

Concept: Dextrin-grafted polymers.

G2b. Adsorption of Surfactants
G2c. Cost-effective Surfactants

Concept: Surfactants from wood pulp lignin-cellulose.

I1a. Detailed Mapping of Sea Bottom

Concept: Digital side-looking sonar, image-processed and with high quality photographic display. Depth calibration by echo-sounding; computer contouring to provide detailed topographic maps (See Ref. 1-1).

I1b. Sea-bottom Characteristics

Concept: Unmanned submersible, towed or free-swimming.

I1c. Sea-Ice Prediction

Concept: Satellite and aircraft imaging, imaging radar, and radiometry. (See I1c in Appendix C).

I2d. Inspection and Manipulation of Equipment on Sea Bottom

Concepts: 1-atmosphere room. Unmanned submersibles with imaging and manipulators.

I2l. Arctic Offshore Communication

Concepts: Marisat. Marine communication satellites with better arctic coverage.

B. TECHNOLOGY BASE

For some other significant petroleum extraction problems, specific concepts based on aerospace technology were not identified, but aerospace appears to provide a technology base which could be utilized to advantage. These problems include:

E2c. Logging Sensors for Use During Drilling

Aerospace technology: Sensors, electronics, instrumentation for remote and hostile environments.

E2f. Distinguished Hydrocarbons from Water by Borehole Measurements

Aerospace technology: Remote measurements of electrical and radio-chemical properties.

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E3a. Measurements from Bottom of Holes during Drilling
E3b. Transmission of Logging Data to the Surface
E3c. Transmission of Downhole Data during Production

Aerospace technology: Telemetry. Telecommunications. Coaxial cables, waveguides, fiber optics. System engineering.

H2a. Gas Compression

Aerospace technology: High capacity reliable pump technology.

C. FINDINGS

A further look would be worthwhile at the possible use of the aerospace concepts listed to help solve the above petroleum production problems.

SECTION 17

RECAP AND PLANS

A. RECAP

The work performed can be summed up as follows:

(1) In discussions during this study, members of the petroleum industry and petroleum service industry identified a large number of problems in the areas of extraction and reservoir engineering.

(2) Preliminary assessment indicated that aerospace techniques may be of help in solving some of the significant problems.

(3) Further consideration led to a number of concepts which employ aerospace techniques to approach these problems.

(4) The following concepts have been examined in a preliminary way, as part of this study:

Problem	Concept
Determining reservoir inhomogeneties and position of induced fractures, fire location, and flood fronts.	• Hole-to-hole seismic tomography.
Determining oil saturation, horizontal and vertical permeability, porosity, and other reservoir properties away from borehole.	• Side-hole drilling.
Perforating deep holes, and deep into formation.	• Multiple side-hole drilling.
Downhole pressure measurements at high temperatures.	• Variable-capacitance gage. • Resistance strain-gage of sputtered thin films.
Thermal stresses and heat losses in steam injection wells.	• Prefabricated doubled-walled tubing with insulation between walls. • Running cooling water down annulus.

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Problem (contd)	Concept (contd)
Non-polluting heat to generate injection steam.	• 2-stage combustion, scrubbing between stages. • Desulfurizing crude with chlorine. • Solar heat (not economic).
Seals and flexible components for downhole use.	• Cross-linking or glass reinforcement to increase high-temperature strength. • Incorporating flexible units into rigid high-temperature polymers.
Long-life downhole drill motor.	• Assist proprietary efforts with components and materials based on aerospace technology.

(5) The following were not examined in this study, but have been the subject of other work.

Problem	Concept
Reduction in drilling costs.	• High pressure drilling. • Automated drilling. • Vibratory drilling. • Combustion-fracture drilling. • Long-stroke screw-actuated mud pump.
Logging for fracture detection.	• Acoustic back-scatter log. • Hole-to-hole seismic tomography.
Measuring stresses in rock.	• Measuring deformation when borehole wall is cut.

(6) The above concepts appear technically feasible. Some seem to offer very attractive cost savings.

(7) The following concepts were identified but not further examined:

Problem	Concept
Transmission of drilling and logging data to central computer.	• Error-correcting codes. • Public service communications satellite.
Reservoir modeling.	• NASTRAN finite element method. • Inversion of production data.
Stability and cost of polymer solutions.	• Dextrin-grafted polymers.
Adsorption and use of surfactants.	• Surfactants from wood pulp lignin-cellulose.
Detailed maps of sea bottom.	• Digital sonar, image-processed, displayed as photomosaics and topo maps.
Sea-bottom characteristics.	• Unmanned submersible.
Sea-ice prediction.	• Satellite imaging, radar, and radiometry.
Inspection and manipulation of sea bottom equipment.	• 1-atmosphere room. • Unmanned submersibles with imaging and manipulation.
Arctic offshore communication.	• Marisat. • Marine communication satellite with better arctic coverage.

(8) Aerospace technology also appears applicable to the following significant problems, but the effort did not include identifying specific concepts for their solution:

Transmission of downhole data to surface during drilling, logging, and production.

Logging sensors for use during drilling.

Distinguishing hydrocarbons from water by borehole measurements.

Gas compression.

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B. PLANS

This report concludes the study effort funded by the NASA Office of Energy Programs. Any further development of the concepts outlined will depend on the interest of government or private organizations in supporting further work.

The concepts have been developed only to the extent detailed in this report. Some of the concepts could now be taken up by the petroleum and service industries for further development. Others would probably require further participation by their designers. All would need development and demonstration as indicated in the report before they could enter service.

NASA's ultimate goal in initiating this study was to attain routine use of aerospace technology in petroleum extraction; this study was pursued to that end. NASA and JPL will therefore actively encourage those interested in further development and utilization of the concepts which emerged from this study, and would be pleased to assist or participate in further work.

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APPENDIX A

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APPENDIX B

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PETROLEUM PRODUCTION PROBLEMS

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This Appendix lists the petroleum extraction problems mentioned by industry, university, and governmental sources. It contains one page per problem, with the preliminary evaluation by the JPL study team, made during Phase 1 of the study.

PROBLEM LIST

A. DRILLING

1. Lower Cost Drilling

A1a. Reduction in Drilling Costs
A1b. Long Life Downhole Drill Motor
A1c. Longer Life Drill Bits

2. Drilling Fluids

A2a. Improved Drilling Fluids

B. WELL COMPLETION

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B1a. Perforation of Casings

2. Sand Control

B2a. Sand Control

3. Flow in Pipes

B3a. Flow Regime Recognition

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3. Corrosion

C3a. Hydrogen Sulfide Corrosion
C3b. Carbon Dioxide Corrosion
C3c. Saltwater Corrosion
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D. STIMULATION

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D1b. Damaged Zone Around Well Bore
D1c. More Effective Explosive Fracturing
D1d. Massive Fracturing of Plastic Rocks
D1e. Determining Position of Induced Fractures
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D1g. Predicting Position of Induced Fractures

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G2b. Adsorption of Surfactants
G2c. Cost-Effective Surfactants

3. Density Control

G3a. Control of Effective Density of Injected and Generated Gases

4. Permeability Control

G4a. Permeability Inhomogeneity
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G4c. Chemical Plugging During Thermal Recovery

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H2a. Gas Compression

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2. Design and Operations

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2. Institutional and Legal

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K. NEW EXTRACTION METHODS

1.

K1a. Flooding Method for Enhanced Gas Recovery
K1b. New Methods for Enhanced Recovery of Oil
K1c. In-Situ Refining

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A1a REDUCTION IN DRILLING COSTS

A.	Problem:	Need faster, more efficient methods of drilling holes.
B.	Need/ significance:	Drilling costs have rapidly increased during the past few years. These costs are a significant factor in developing new fields as well as a major factor in enhanced recovery projects. Generally speaking, reduced drilling cost would make some presently uneconomic reserves available.
C.	Present techniques:	The only major method presently utilized in the USA is the rotary drilling system of turning a 3 cone bit from the surface, using a long string of drill pipe to transmit power and drilling fluid to the bottom of the hole. Downhole drill motors are used but limited to directional drilling because of short life and slow penetration rates. ERDA-supported work is under way on development of better downhole motors.
D.	Matching aerospace technology:	High pressure technology. Automatic control. Vibration control.
E.	Concepts for consideration:	Improved high pressure drilling. Automated drill rigs. Improved downhole drill motors. Vibratory drilling. Chipping rock with pulsed exhaust from downhole rocket engine.
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	5-10

A1b LONG LIFE DOWNHOLE DRILL MOTOR

A.	Problem:	Developing a downhole drill motor that can last long enough to compete economically with the conventional rotary drilling system.
B.	Need/ significance:	Downhole drill motors promise reduced cost because they eliminate friction losses of energy by the drill string rotating against the wall, and they permit more ready utilization of electrical signaling and control along the length of the borehole during drilling. This in turn permits more efficient drilling and minimizes the chances of blowout, etc. Also, with downhole motors it is much easier to promptly detect and control the direction of the borehole during drilling. However, the downhole motors that have been tried so far have not had adequate life or low enough maintenance cost to make them competitive with conventional drilling. Seal problems have been especially important.
C.	Present techniques:	Conventional rotary drilling systems are used in all but deviated holes. The directional drilling is done by use of a downhole motor to deviate the hole, but conventional drilling is again used following the deviation operation. A system using a downhole electric motor is being tested with ERDA support.
D.	Matching aerospace technology:	Mechanical engineering. Vibration analysis. Fluid mechanics. Stress analysis.
E.	Concepts for consideration:	Downhole mud turbine with improved design, anchoring to wall of borehole.
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	High to moderate
I.	Years until demonstration:	Indeterminate

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A1c LONGER LIFE DRILL BITS

A.	Problem:	Improve present drill bits for longer life at increased weight, rotation speed, and temperature.
B.	Need/ significance:	The present drill bits have a lifetime determined by weight on the bit, rotation speed, formation characteristics and temperature. These factors limit penetration rate and are the major factors in the cost of drilling deep wells. In addition, having to remove a worn-out bit requires added rig time which increases the total drilling costs. An improved bit would reduce these drilling costs.
C.	Present techniques:	Examples of present bit life in a deep (20,000 ft) well in the West Texas area show that a bit can drill as little as 100 ft, at a rate of 8 to 10 ft per hour. Longer bit life would result in a significant savings for each well drilled, due to reduced down time, and a major contribution to cost savings in the some 45,000 wells drilled each year in the USA.
D.	Matching aerospace technology:	Mechanical, materials, and lubrication engineering.
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	2-5

A2a IMPROVED DRILLING FLUIDS

A.	Problem:	Drilling fluids that provide hole-wall stability, pressure control, drill pipe and bit lubrication and cooling, with less damage to formations in the vicinity of the wellbore and less reduction in drilling rates due to chip hold down or inefficient chip removal from the wellbore.
B.	Need/ significance:	Lower cost of drilling and reduction in production losses would result if drilling fluid systems could be improved to reduce fluid loss into formations and to perform at higher temperatures.
C.	Present techniques:	A variety of water-based and oil-based suspensions are in use. Considerable research and development effort is being expended to improve drilling fluids. Attempts to find and produce economical additives and new systems have resulted in some improvement in thermal stability, and reduction in formation losses and in damage to formations.
D.	Matching aerospace technology:	Fluid mechanics. Lubrication.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

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B1a PERFORATION OF CASINGS

A.	Problem:	A better method of perforating casing and cement in deep, hot producing formations is required.
B.	Need/ significance:	Present perforation methods are limited to a few inches depth of penetration into the formation. It would be beneficial to penetrate the formation several feet to increase production. Little research-type work is in progress on explosive perforation techniques.
C.	Present techniques:	Multiple shaped-explosive charges are currently used to perforate casing and cement, but on a pragmatic basis. The results are usually but not always satisfactory. At greater depths there is evidence of lack of penetration. Also, high temperatures reduce the reliability of explosive detonations. Laser perforation has been proposed.
D.	Matching aerospace technology:	Shaped charges. Lasers. Combustion technology.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low to moderate
I.	Years until demonstration:	5

B2a SAND CONTROL

A.	Problem:	Entrance of formation sand into the well bore during production of oil and gas is a problem common with loose, unconsolidated sand formations. This problem is more severe with enhanced recovery processes such as water flood, thermal recovery, etc. because of the increased volume of fluid flowing.
B.	Need/ significance:	Sand entering into the well bore can plug the casing perforations, abrade the pump, tubular goods, and surface equipment, and plug the well bore. All of these problems result in costly loss of production and expensive workover operations to clean up the hole and repair damaged equipment.
C.	Present techniques:	The oil industry has developed a number of techniques to control the loose formations. These include slotted or perforated lines, sand and gravel packings, cements and polymers. All of the techniques have limitations depending upon flow volume, pressures, temperatures, formation characteristics and hole geometry.
D.	Matching aerospace technology:	Polymer chemistry and engineering. Soil mechanics.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	3-5

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B3a FLOW REGIME RECOGNITION

A.	Problem:	Recognizing the particular flow regime for two-phase flow in pipes.
B.	Need/ significance:	In petroleum extraction two-phase flow in pipes, both vertical and horizontal, is very common. There are a number of different flow regimes, each of which has a different set of equations governing the flow. To properly engineer the pipe system, it is essential to understand which regime will be in effect for any particular set of conditions, since the different sets of equations give significantly different results. This is at present often difficult and over design is likely on account of the uncertainty.
C.	Present techniques:	Empirical methods
D.	Matching aerospace technology:	Fluid flow
E.	Concepts for consideration:	
F.	Importance to industry:	Low
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

C1a THERMAL STRESS IN CASINGS

A.	Problem:	Thermal stress and strain in casing during some enhanced recovery operations causes problems and limits depths of operation.
B.	Need/ significance:	During injection of steam, differential thermal expansion occurs between the steel liner and the surrounding cement. This tends to destroy the bond and fracture the cement. This opens uncontrolled paths outside the casing and can lead to loss of oil and gas, flow of water into the well or producing formation, pollution of ground water, safety hazards, etc.
C.	Present techniques:	Sometimes casing is pre-stressed. Insulation between the tubing and the casing has had little success. Casing with expansion bellows joints has been tried, with poor results.
D.	Matching aerospace technology:	Systems engineering. Mechanical engineering. Design and materials for rocket engines. Composite structures. Elastomers. Solid propellants.
E.	Concepts for consideration:	Better insulation. Flexible cement.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	High to moderate
I.	Years until demonstration:	3-5

C1b HIGH TEMPERATURE RUBBER

A.	Problem:	Rubber components fail at down-hole temperatures.
B.	Need/ significance:	Many downhole devices - logging tools, cables, packings, downhole drill motors, etc. - use rubber components as seals, sleeves, electrical insulation, flexible elements and so forth. At temperatures above 100°C these components are likely to fail or have short life.
C.	Present techniques:	
D.	Matching aerospace technology:	Solid-propellant technology: polymer chemistry; design of composite (reinforced) structures; computer modeling of composite structures. High temperature elastomers.
E.	Concepts for consideration:	High temperature elastomers. Computer-aided design using cord reinforcement. Work is under way at a NASA laboratory on the general problem of high temperature elastomers.
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate to high
H.	Likelihood of significant aerospace contribution:	moderate to high
I.	Years until demonstration:	2

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C2a QUALITY CONTROL

A.	Problem:	Quality control of tubular goods, valves and controls.
B.	Need/ significance:	As wells are drilled and produced at greater depths and in less accessible locations, the need for lower failure rates becomes more important.
C.	Present techniques:	Statements about properties from approved manufacturers are usually accepted without test, and free replacement is expected if failure occurs. For critical parts to be used in remote locations, certification of compliance with specifications is sometimes required.
D.	Matching aerospace technology:	Quality control. Fracture mechanics. Automated flaw detection.
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Moderate to high
I.	Years until demonstration:	2

C2b DEEP WELL PUMP

A.	Problem:	Improved pumps for deep wells.
B.	Need/ significance:	As the more readily available reservoirs are depleted, the need to tap the deeper supplies will become increasingly important. Pumps with improved efficiency and requiring less maintenance are needed, particularly for depths greater than 10,000 ft or pressures greater than 10,000 psi.
C.	Present techniques:	Hydraulic and electric pumps are used. Sucker rods of light, high strength, polymer are being tried.
D.	Matching aerospace technology:	Pump experience. Liquid rocket propulsion. Mechanical engineering. Fluid mechanics.
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Moderate to low
I.	Years until demonstration:	5

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C2c ELECTRICAL LEAD-THROUGHS FOR SEA BOTTOM USE

A.	Problem:	Lead-throughs for use at the sea bottom.
B.	Need/ significance:	When offshore wells are completed at the sea bottom, measurements at the well head are needed. Electrical leads must then be brought out of the well-head compartment and connected to cables running to the surface. Water leakage tends to occur at the lead-throughs and connections.
C.	Present techniques:	
D.	Matching aerospace technology:	
E.	Concepts for consideration:	Acoustic couplers
F.	Importance to industry:	Low
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low to moderate
I.	Years until demonstration:	2

C2d CHEAPER WELL PIPING

A.	Problem:	Reducing the cost of well casing, tubing and couplings.
B.	Need/ Significance:	The cost of piping is a significant portion of the total cost of a completed well. Both mechanical stresses and corrosion must be resisted.
C.	Present techniques:	Use steel, to API standards.
D.	Matching aerospace technology:	Materials and mechanical engineering.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

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C3a HYDROGEN SULFIDE CORROSION

A.	Problem:	Hydrogen sulfide tends to corrode casings, valves, and other underground equipment constructed from normal steels. Hydrogen embrittlement also occurs.
B.	Need/ significance:	The need is for a relatively cheap material (or design) which is non-reactive with H_2S, non susceptible to hydrogen embrittlement, and has the strength characteristics of steel.
C.	Present techniques:	Special corrosion-resistant steels have been used but are weak and expensive. Plastic-lined steel pipes, as currently designed, have problems at joints and with delamination.
D.	Matching aerospace technology:	Materials engineering.
E.	Concepts for consideration:	Cladding. Electrolytic protection.
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate to high
H.	Likelihood of significant aerospace contribution:	Moderate to low
I.	Years until demonstration:	5-10

C3b CARBON DIOXIDE CORROSION

A.	Problem:	CO_2 used in enhanced recovery operations causes accelerated corrosion of steel casings, valves, etc.
B.	Need/ significance:	CO_2 flooding is a proven enhanced recovery technique which would be more useful if the corrosive effects could be reduced.
C.	Present techniques:	Replacement as required.
D.	Matching aerospace technology:	Materials engineering.
E.	Concepts for consideration:	Cladding. Electrolytic protection.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate to low
H.	Likelihood of significant aerospace contribution:	Moderate to low
I.	Years until demonstration:	5-10

C3c SALTWATER CORROSION

A.	Problem:	Corrosion due to sea water.
B.	Need/ significance:	Significant difficulties have been encountered with the corrosion of marine risers, the pipes that bring oil from sub-sea wells to above-surface storage or transport facilities. The difficulties have been found particularly near the air-water interface, especially where violent spray strikes the risers.
C.	Present techniques:	Wave protection can be used. Non-corrosive materials or treatments. Ship techniques.
D.	Matching aerospace technology:	Materials engineering.
E.	Concepts for consideration:	Cladding. Electrolytic protection.
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

C3d CORROSION INHIBITORS

A.	Problem:	Improvement of corrosion inhibitor performance at high temperature and pressure conditions.
B.	Need/ significance:	Corrosion inhibitors are needed that have improved performance characteristics in very hot and in geo-pressured wells. Corrosive effects of H_2S, sulfates, and CO_2 in both liquid and gas phases must be controlled.
C.	Present techniques:	Phosphates and polyacrylates are used.
D.	Matching aerospace technology:	Materials engineering.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	Indeterminate

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D1a PRODUCTION FROM LOW-PERMEABILITY RESERVOIRS

A.	Problem:	How to obtain economic rates of production from low-permeability reservoirs.
B.	Need/ significance:	A large fraction of the known U.S. petroleum resources is in low-permeability reservoirs from which it is very difficult or uneconomic to extract the petroleum. Included is oil in siltstone, reef, chalk, and other fine-grained reservoirs, and gas in many deep tight reservoirs. If better methods could be found to open up flow paths in these reservoirs, production could be greatly increased.
C.	Present techniques:	Chemical treatments, such as acidizing, and explosive fracturing. These are so far limited to a small radius from the well. Hydraulic fracturing. Considerable work is underway on massive hydraulic fracturing, especially in gas reservoirs, under both company and ERDA funding. Efforts are also underway on combinations of hydraulic and explosive fracturing, and on combinations of explosive and propellant fracturing. Suggested techniques, for gas reservoirs, include mining and treatment with H_2.
D.	Matching aerospace technology:	Propellants and explosives. Mechanical engineering. High pressure pumps.
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	5

D1b DAMAGED ZONE AROUND WELL BORE

A.	Problem:	Improved techniques to overcome damage to the zone around the well bore.
B.	Need/ significance:	Drilling and completion are sometimes done by techniques that damage the zone around the well bore, usually by reducing its permeability. This may greatly reduce the rate of production from the well, or if it is an injection well, the rate of injection.
C.	Present techniques:	Chemical methods, including acidizing. Fracturing methods, hydraulic and explosive.
D.	Matching aerospace technology:	Mechanical engineering. High pressure pumps. Propellants.
E.	Concepts for consideration:	
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low to moderate
I.	Years until demonstration:	5

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D1c MORE EFFECTIVE EXPLOSIVE FRACTURING

A.	Problem:	Better ways to get explosive out into the formation for fracturing.
B.	Need/ significance:	There is current interest in explosive fracturing techniques that use liquid explosive placed in fractures previously induced. Better ways to get the explosive out into the formation should result in more extensive fracturing and consequently improved production.
C.	Present techniques:	Preliminary fractures are produced hydraulically and liquid explosive driven into them by pumping water behind the explosive.
D.	Matching aerospace technology:	Propellants
E.	Concepts for consideration:	
F.	Importance to industry:	Low to moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

D1d MASSIVE FRACTURING OF PLASTIC ROCKS

A.	Problem:	Massive fracturing of rocks that tend to behave plastically.
B.	Need/ significance:	For gas recovery from tight reservoirs, hydraulic fracturing is reasonably satisfactory if the rock behaves brittlely at low strain rates; long fractures are produced. In rock more plastic at low strain rates, short wide fractures are produced that give poor recovery. Besides hydraulic fracturing, explosive fracturing can be used. The resulting strain rate and stresses are too high: the rock is shattered locally.
C.	Present techniques:	As above
D.	Matching aerospace technology:	Propellants
E.	Concepts for consideration:	
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

D1e DETERMINING POSITION OF INDUCED FRACTURES

A.	Problem:	Determining the position of artificially induced fractures.
B.	Need/ significance:	Fracturing the rock hydraulically or by explosives is commonly used to increase production from low-permeability reservoirs. To properly engineer continuing fracturing efforts in a field, the position of the induced fractures needs to be known. Especially important is the vertical extent of the fractures, with respect to the producing formation, away from the boreholes used in inducing the fractures. The horizontal extent and direction of the fractures should also be known.
C.	Present techniques:	Vertical temperature profile at the borehole: this gives only the vertical extent <u>at</u> the borehole. Listening to the fracture as it is formed, with phones on the surface or in boreholes. This is still experimental. A difficulty is the noise produced by hydrofracing equipment or an explosive fracture source. Experimentation is underway on tilt meter indications of the earth position during hydrofracturing. Analysis techniques for interpretation of the findings have not been developed. Electrical resistivity techniques, measuring from the surface and downhole, are also being tried.
D.	Matching aerospace technology:	Remote measurements
E.	Concepts for consideration:	Acoustic backscatter fracture log. Faster pumping equipment.
F.	Importance to industry:	Moderate to high
G.	Importance to ERDA:	Moderate to high
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	2-3

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D1f CONTROLLING POSITION OF INDUCED FRACTURES

A.	Problem:	Controlling the position of artifically induced fractures.
B.	Need/ significance:	Fracturing the rock hydraulically or by explosives is commonly used to increase oil or gas production from low permeability reservoirs. To optimally increase production, the position of the induced fractures should be controlled. Most important is controlling the vertical extent of the fracture, so that it stays within the producing reservoir and does not extend into the underlying or overlying impermeable beds that seal the reservoir. If the latter occurs, much fracturing energy is wasted and serious leakage out of or into the reservoir may result.
C.	Present techniques:	Massive hydrofracing. To limit the vertical extent: pump slowly to keep the strain rate and stress level low and control the viscosity of the fracturing fluid. Chemical explosives: if the explosives are in the borehole, effect is too local. Experiments in placing explosives out in prior hydrofractures have not yet given good production. Nuclear explosives: experiments with these have not given good production.
D.	Matching aerospace technology:	Propellants. Shaped changes.
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate to high
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

D1g PREDICTING POSITION OF INDUCED FRACTURES

A.	Problem:	Predicting the position of artificially induced fractures.
B.	Need/ significance:	Fracturing the rock hydraulically or by explosives is commonly used to increase production from low permeability reservoirs. To properly engineer fracturing efforts, it is important to be able to predict the positon of the fractures. Most critical is whether the fracture will propagate only in the producing formation or will extend into underlying and overlying impermeable beds that seal the reservoir. If the latter occurs, much fracturing energy will be wasted and serious leakage out of or into the reservoir may occur. The mechanical properties of the various beds as well as the fracture technique used will affect the result.
C.	Present techniques:	The extent of the fracture from the well bore depends upon several parameters including pumping flow rate, characteristics of the formation, fracturing fluid properties, and volume of injected fluid. Prior to the fracturing operation, these factors are considered and an optimum program developed. Since there are a number of unknowns which have to be estimated, the results are not always as expected.
D.	Matching aerospace technology:	Stress analysis. Fracture mechanics.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high
G.	Importance to ERDA:	Moderate to high
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

E1a WELL CORE SAMPLING AND ANALYSIS

A.	Problem:	Well formations are sampled by coring a cylinder of rock during drilling. The core sample is brought to the surface and analyzed in a lab for fluid content and rock properties. The problem is that the core sample is sometimes changed by the drilling, washing by drilling fluids, and removal to surface. It is necessary to attempt to restore subsurface conditions in the lab tests and this is not always successful.
B.	Need/ significance:	Accurate measurements made in the reservoir would be most desirable. If this were not economically or technically feasible, improved methods of coring and subsequent handling of the core sample should be developed to better preserve subsurface conditions.
C.	Present techniques	Attempts have been made to remove cores at bottom hole pressure. They are sometimes frozen at the well head to reduce subsequent fluid transfer. Work is under way on techniques of coring without using mud. Analyzing the core without removing the core from the well bottom has been suggested.
D.	Matching aerospace technology:	Remote manipulation. Remote measurements.
E.	Concepts for consideration:	Side wall drilling and in situ measurements.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7.

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E1b MEASURING FRACTURE TOUGHNESS OF ROCKS

A.	Problem:	Determining the fracture toughness of reservoir rocks and of the rocks immediately above and below the reservoir.
B.	Need/ significance:	To evaluate and plan possible fracturing operations, especially for low permeability gas reservoirs, it would be very helpful to know the pertinent mechanical properties of the reservoir rocks and of the rocks sealing the reservoir above and below. These properties should be determined at temperature, lithostatic pressure, hydrostatic pressure, fluid content and loading conditions corresponding to those in situ.
C.	Present techniques:	Mechanical tests are sometimes made on cores, but it is difficult and expensive to reproduce in situ conditions.
D.	Matching aerospace technology:	Materials testing. Environmental testing.
E.	Concepts for consideration:	Pressurized high temperature multi-axial mechanical test equipment.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	High
I.	Years until demonstration:	3-5

E2a HIGH TEMPERATURE DOWNHOLE PRESSURE MEASUREMENTS

A.	Problem:	Instrumentation to measure pressure changes to 0.01 psi at 3000 psi and 500°F, downhole. Also, instrumentation to measure temperature under these conditions.
B.	Need/ significance:	For flow and pressure-pulse testing of wells. Total pressure change during test is often only 0.5 psi; accuracy of results depends on measuring this change vs. time with high accuracy.
C.	Present technique:	Hewlett Packard quartz pressure gauges, said to be good to 300°F only.
D.	Matching aerospace technology:	Instrumentation. Magnetic pressure sensors. Materials. Electronic components.
E.	Concepts for consideration:	Magnetic sensors using high temperature materials and electronics.
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate for petroleum; high for geothermal.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	3-5.

E2b HIGH TEMPERATURE WELL LOGGING

A.	Problem:	High pressures and high temperatures encountered in deep holes render electric logging tools inaccurate or inoperative because of degradation of elastomers and electronic components.
B.	Need/ significance:	Although the present number of deep hot wells, both petroleum and geothermal, is relatively small, the future needs will be greater. Accurate data from the deep holes are even more important than for shallower holes because of the high cost of deep holes.
C.	Present techniques:	Where the size of the hole permits larger diameter tools, the instruments are placed in Dewars. Special efforts are made to keep the time of the run as short as possible. Sometimes the logging tools are cooled by circulating drilling fluid.
D.	Matching aerospace technology:	Materials. Polymers. Solid propellants. Electronics.
E.	Concepts for consideration:	ERDA has several research contracts placed to develop temperature resistant electronic components and elastomers. Some of this materials work is being done at aerospace laboratories. Improved mechanical and materials design of seals and other mechanical components.
F.	Important to industry:	Moderate to high
G.	Importance to ERDA:	Moderate to high for petroleum; high for geothermal.
H.	Likelihood of significant aerospace contribution:	High
I.	Years until demonstration:	1-2

E2c LOGGING SENSORS FOR USE DURING DRILLING

A.	Problem:	Various logging sensors are needed for use during drilling.
B.	Need/ significance:	To guide and control drilling, and to reduce drilling and logging costs, logging during drilling is needed. Techniques for doing this are being introduced, but suitable sensors are not available for many desired quantities. For example, with one technique, only hole direction and perhaps electric logs are available. Especially needed are sensors for weight on the bit, drilling torque at the bit, vibrations at the bit. Sensors for other conventional logs are also needed.
C.	Present techniques:	For drilling parameters, surface measurements only. For other parameters, interrupt drilling and run separate logs. Some work is underway with ERDA support.
D.	Matching aerospace technology:	Instrumentation for hostile environments. Sensors. Electronics.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	5

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E2d DOWNHOLE PERMEABILITY MEASUREMENTS

A.	Problem:	A technique is needed to measure the permeability of formations downhole.
B.	Need/ significance:	Permeability is one of the key parameters in determining whether a particular geological horizon will be tested for production. The inability to accurately predict formation permeability can result in potential producing zones being incorrectly categorized as uneconomic. Conversely, over-optimistic estimates of permeability can result in expensive and fruitless well completion efforts.
C.	Present techniques:	Direct means of measuring downhole permeability are limited. Logs may be used to indicate porosity, but not permeability. Permeability can be measured on cores; these are expensive, not always taken at the level of interest, sometimes fall apart, and may be changed by removal from the well. Flow tests indicate permeability but are time-consuming and expensive.
D.	Matching aerospace technology:	Remote measurements. Remote manipulation.
E.	Concepts for consideration:	Side wall drilling and flow test between two side holes. These holes can be at the same level for horizontal permeability; above each other for vertical permeability.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7.

E2e IMPROVED LOGGING METHOD FOR DETECTION OF FRACTURES

A.	Problem:	Better logging method to find tight fracture patterns tens of feet out into rock surrounding borehole and to measure their spacing and thickness.
B.	Need/ significance:	Particularly in deep fine-grained reservoirs, fractures govern fluid flow and also the pattern of subsequent artificial fracturing. Fracture patterns significantly affect cost of and recovery from secondary/tertiary recovery efforts. Data on fracture patterns and thickness are needed to evaluate and plan secondary/tertiary recovery. They may also help initial reservoir assessment.
C.	Present techniques:	Camera, cores, and sonic log. Neither camera nor sonic log is good at showing tight fractures. Camera and cores are limited to the borehole; the borehole fracture pattern may be unrepresentative of surrounding material since drilling the hole and removing the core changes the stress pattern.
D.	Matching aerospace technology:	Acoustics. Electronics. Radar. Sonar.
E.	Concepts for consideration:	Improved acoustic technique (sonar), emphasizing backscattering and imaging.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate to high.
I.	Years until demonstration:	5.

E2f DISTINGUISHING HYDROCARBONS FROM WATER BY BOREHOLE MEASUREMENTS

A.	Problem:	Better technique to distinguish hydrocarbons from water by borehole measurements.
B.	Need/ significance:	The composition of the formation fluid must be determined to evaluate the formation.
C.	Present techniques:	Electric logs, which measures resistance, or sampling the fluid as it flows into the hole. Present electric logs, it is stated, do not always adequately distinguish formation water from oil or gas. The same is true of nuclear logs. Fluid sampling gives the composition only at one depth per sample and it is difficult to get accurate samples. A dielectric-constant log has been tried.
D.	Matching aerospace technology:	Electrical measurements. Radio-chemistry measurements.
E.	Concepts for consideration:	Down-hole gravimetry (since oil-bearing strata are generally less dense than water-bearing).
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5

E2g MEASURING STRESSES IN RESERVOIR AND BOUNDING ROCKS

A.	Problem:	Measuring stresses existing in the reservoir rock and in the rock bounding the reservoir above and below.
B.	Need/ significance:	To evaluate and plan possible fracturing operations, especially for low-permeability gas reservoirs, it would be helpful to know the stresses existing in the reservoir rock and in the rocks immediately above and below the reservoir.
C.	Present techniques:	None.
D.	Matching aerospace technology:	Stress measurement and analysis. Remote measurements in difficult environments. Instrumentation.
E.	Concepts for consideration:	From a borehole, cutting or drilling away material and measuring resulting deformations. One device to do this has been developed by an aerospace company.
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	High
I.	Years until demonstration:	0?

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E2h MEASURING FIRE LOCATION

A.	Problem:	Methods of determining the location of the fire during thermal recovery by fire flooding are needed.
B.	Need/ significance:	Determination of the fire location is needed for more effective control of fire flood recovery operations.
C.	Present techniques:	The location of the fire is predicted by using models.
D.	Matching aero-space technology:	Remote sensing. Instrumentation. Acoustic tomography. Modeling.
E.	Concepts for consideration:	Passive seismic. Seismic reflection. Downhole seismic velocity. Downhole acoustic tomography. Better modeling, utilizing temperature measurements at production wells.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate to high
I.	Years until demonstration:	5-10

E2i MONITORING OF FLOOD FRONTS

A.	Problem:	Method to monitor the position of flood fronts and gas/water interfaces at repeated intervals or on a continuous basis.
B.	Need/ significance:	Could improve the efficiency of enhanced recovery operations by knowing position of the flood front in the reservoir, thus allowing for corrective controls to be applied prior to unwanted breakthroughs.
C.	Present techniques:	None. Seismic refraction has been suggested.
D.	Matching aerospace technology:	Remote sensing. Instrumentation. Acoustic tomography.
E.	Concepts for consideration:	Downhole acoustic tomography. Downhole seismic velocity. Seismic refraction.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7.

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E2j METERING POLYMERS

A.	Problem:	Accurate metering of polymers for enhanced recovery.
B.	Need/ significance:	Considerable effort is underway on micellar-polymer floods for enhanced recovery as well as on straight additions of polymers to water for flooding. For proper operation, it is important to meter the amount of polymers added, but this is difficult to do. Present turbine meters do not read accurately for polymer suspensions.
C.	Present techniques:	
D.	Matching aerospace technology:	Sensors. Instrumentation. Liquid propulsion. Flow rate sensors for propellants.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate to high.
I.	Years until demonstration:	3.

E2k MEASUREMENT OF CONCENTRATION OF CORROSION INHIBITORS DOWNHOLE

A.	Problem:	Knowledge of corrosion inhibitors applied at the well bottom is needed before the fluid arrives at the surface.
B.	Need/ significance:	Earlier knowledge would reduce the amounts of inhibitors that need to be applied and thus increase their cost-effectiveness.
C.	Present techniques:	Analysis of fluid to determine concentration and effectiveness can only be done after it has arrived back at the surface.
D.	Matching aerospace technology:	Instrumentation. Remote measurements under hostile environments.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Moderate to high.
I.	Years until demonstration:	3.

E21 MONITORING PRODUCTION DURING CHEMICAL FLOODING

A.	Problem:	Inexpensive monitoring of daily production from each well during chemical flooding.
B.	Need/ significance:	Considerable effort is underway on chemical flooding techniques, such as micellar-polymer flooding, for enhanced recovery. To properly control the operation, it is important to monitor the daily production from each well. This can be quite expensive because of the many wells involved and the very large ratio of water to oil (often > 100 with micellar flooding).
C.	Present techniques:	
D.	Matching aero-space technology:	Instrumentation.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	2-3.

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E3a MEASUREMENTS FROM BOTTOM OF HOLE DURING DRILLING

A.	Problem:	Providing measurements of drilling and geophysical parameters from the bottom of the hole during drilling.
B.	Need/ significance:	Monitoring down-hole parameters during drilling would lead to significant cost savings. It would avoid some of the costly interruptions in drilling now needed to make measurements. High data rates are needed to accommodate measurements of multiple parameters with adequate accuracy and adequate sampling rates. A down-hole power supply for data measurement and transmission will probably also be needed.
C.	Present techniques:	Techniques are under development or being introduced. These include use of water or drilling fluid for hydraulic pulse transmission, using drill pipe as an electrical conductor, using the earth to transmit electrical signals, and attaching an electrical cable inside each length of drill pipe.
D.	Matching aero-space technology:	Telemetry; telecommunications.
E.	Concepts for consideration:	Waveguides.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Low to moderate.
I.	Years until demonstration:	5.

E3b TRANSMISSION OF LOGGING DATA TO THE SURFACE

A.	Problem:	Transmission of logging data up the bore hole to the surface.
B.	Need/ significance:	Well-logging data is either recorded downhole in the sonde or electrically transmitted up a cable for recording at the surface. Both systems have disadvantages. If the recording is downhole, it is not possible to tell at the surface whether the logging tool is operating properly and data are being recorded. If the data are sent up a cable, they may tend to be distorted by cable characteristics. Also, there are major problems with the use of cables at high well temperatures.
C.	Present techniques:	Cables now being used generally contain unshielded wires. The insulation used limits the temperatures at which they can be operated. There is some effort underway to provide cables with higher temperature insulation.
D.	Matching aerospace technology:	Telemetry. Communications. Coaxial cables. Fiber optics. Waveguides.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	2.

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E3c TRANSMISSION OF DOWN-HOLE DATA DURING PRODUCTION

A.	Problem:	Means to transmit data on conditions at the bottom of the hole to the surface during production.
B.	Need/ significance:	Present methods of measuring down-hole parameters generally require interrupting production, lowering instruments, recording data, and removing the instruments. More useful information could be obtained if instruments could be left down-hole and data transmitted continuously during operation. When the producing bed is thick, it would also be desirable to be able to move the instruments, as desired, to scan across the bed.
C.	Present techniques:	Wire line instruments, generally recording the data within the instrument case rather than transmitting it to the surface. The instruments are not designed to be left in the well throughout production.
D.	Matching aerospace technology:	Telemetry. Instrumentation. Communications.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	5.

C-3

E3d TRANSMISSION OF DRILLING AND LOGGING DATA TO AND FROM CENTRAL COMPUTER

A.	Problem:	Inexpensive, error-free transmission of drilling and logging data to and from central computer and central office.
B.	Need/ significance:	As part of an improved computerized drilling system, an improved technique is needed for transmission of drilling data between field computer drill sites (especially marine sites) and central computer. Freedom from transmission errors, adequate channel rates, and low cost are all important. Similar requirements exist for transmission of logging data. For drilling, transmission once a day of a batch of 10,000 words would usually be adequate, but in critical periods real time transmission is needed.
C.	Present techniques:	Multiple radio and telephone links; error rates are high. Marisat links have been suggested but quoted cost is too high. One company does all its logging computing on-site.
D.	Matching aerospace techniques:	Radio communications, satellite communications.
E.	Concepts for consideration:	Public service communications satellites. Error correcting codes. Datafax.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contributions:	High.
I.	Years until demonstration:	2-3.

E4a INTERPRETATION OF WELL-TO-WELL TRACER DATA

A.	Problem:	Better methods of analyzing and interpreting well-to-well tracer data.
B.	Need/ significance:	One of the few accepted methods of measuring flow characteristics of a reservoir is to inject tracers into one well and measure their appearance as a function of time in nearby wells. Most of the attention currently is focused on the time at which the tracer first appears in each well ("breakthrough"). This gives information about the one path of highest permeability between the wells but does not tell much else about the reservoir. Computer methods of analysis and methods of interpretation are needed which focus on the volumetric sweep of the tracer through the reservoir as reflected in the quantity of tracer arriving at the receiving well as a function of time, not just on the breakthrough time.
C.	Present technique:	Computer reservoir modeling and analysis, mostly focusing on breakthrough time.
D.	Matching aerospace technology:	Computer modeling.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	3-5.

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E4b INTERPRETATION OF PRESSURE PULSE DATA

A.	Problem:	Better methods of processing and analyzing pressure pulse data.
B.	Need/ significance:	One of the few accepted methods of measuring reservoir flow characteristics is applying pressure pulses to one well and measuring the resulting pressure changes at nearby wells.
C.	Present techniques:	Computer modeling of the reservoir and its flow response to pressure pulses. As now performed this method leaves something to be desired, particularly in the area of processing and analyzing data.
D.	Matching aero-space technology:	Computer modeling. Correlation methods.
E.	Concepts for consideration:	Correlation methods.
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	2-3.

E4c IMPROVED INTERPRETATION OF ELECTRIC WELL LOGS

A.	Problem:	Electric well logs sometimes indicate only water in formations which flow tests show contain oil.
B.	Present techniques:	Computer and hand correlation of various types of logs can usually show whether hydrocarbons are present.
C.	Need/ significance:	Accurate and reliable location of hydrocarbons is important, especially in more expensive wells. Missing an oil-bearing formation is very costly. Accurate location is important for future casing perforation.
D.	Matching aerospace technology:	Pattern recognition. Data analysis.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	

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E4d CORRECTING WELL-LOGS FOR DRILLING-MUD PROPERTIES

A.	Problem:	The actual well hole diameter and the wall porosity vary due to strata differences. The drilling mud that is within the hole and in the wall surface pores thus varies in thickness. This introduces errors in well-log readings.
B.	Need/ significance:	Higher quality well-logs will reduce costs and probably increase the amount of petroleum found.
C.	Present techniques:	These errors are either ignored, or corrected by empirical formulas, or their effect is sometimes mitigated by mechanical means. In one logging system requiring electrical contact with the wall (very short measuring length), the electrodes are extended out through the mud to contact the wall directly. The mud contained within the pores of the wall still introduces a significant error.
D.	Matching aerospace technology:	Remote sensing. Data analysis.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	

E5a AUTOMATIC CONTROL OF MICELLAR FLOODING OPERATION

A.	Problem:	Inexpensive method of automatic control of micellar flooding operation.
B.	Need/ significance:	To apply micellar flooding efficiently as a means of enhanced recovery, good control of the injected fluids is necessary during the operation. However, good automatic control for this purpose is expensive.
C.	Present techniques:	
D.	Matching aerospace technology:	Automatic control.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate to low.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	2-3.

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E5b MEASURING AND CONTROLLING FLUID FLOW IN ENHANCED RECOVERY

A.	Problem:	Measuring and controlling fluid flow into, within, and out of the reservoir in enhanced recovery operations.
B.	Need/ significance:	For efficient production and high recovery, the flow of fluids into, within, and out of the reservoir should be known and controlled. Better methods are needed.
C.	Present techniques:	Flow meters, tracers, analysis.
D.	Matching aerospace technology:	Automatic control. Instrumentation for hostile environments. Liquid rocket propulsion.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	2-3.

E5c CONTROL OF DOWN-HOLE PUMPS AND VALVES

A.	Problem:	More reliable surface control of down-hole pumps and valves is needed.
B.	Need/ significance:	Present techniques for controlling down-hole pumps and valves are not very satisfactory. The down-hole equipment for receiving and implementing control signals is not reliable enough. When malfunctions occur, the replacement procedure is expensive.
C.	Present techniques:	Acoustic pulses on piping. Pressure pulses in water lines.
D.	Matching aerospace technology:	Automatic control systems. Remote control of pumps and valves.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	3-5.

E5d MAINTAINING DRILL-SHIP POSITION

A.	Problem:	In some locations and some wind and sea conditions, excessive power is needed to maintain ship position during drilling.
B.	Need/ significance:	Adds to drilling cost.
C.	Present techniques:	Drill ships and barges, surface platforms, semi-submersibles. Anchoring.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

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F1a DETERMINING RESIDUAL OIL SATURATION

A.	Problem:	Determining residual oil saturation accurately.
B.	Need/ significance:	The residual oil saturation in a reservoir is critical to the economic evaluation of enhanced recovery operation. For example, with 25% residual oil saturation, enhanced recovery may be worthwhile. With 20%, it may not. Present techniques do not reliably provide such accuracy.
C.	Present techniques:	Coring: Cores tend to interchange fluids with the drilling mud. Their hydrocarbon content is affected by pressure and temperature changes when the core is removed from the well. Cores are now sometimes removed at bottom-hole pressure and are sometimes frozen at the well top to reduce subsequent fluid transfer. Work is underway on techniques of coring without using mud. Analyzing the core without removing the core from the well bottom has been suggested. Logging: Accuracy and reliability are inadequate. Present logs do not always distinguish oil from water reliably. Production history: Production history during primary and secondary recovery operations can indicate the residual oil content, but not with great accuracy. Work on this problem is planned in the ERDA 5-year program. Some work is underway.
D.	Matching aerospace technology:	Instrumentation. Computer modeling. Pattern recognition.
E.	Concepts for consideration:	Sidewall drilling with sampling and measurements between two side holes.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7.

F1b MEASURING POROSITY AND OIL SATURATION AWAY FROM BOREHOLES

A.	Problem:	Methods of measuring reservoir porosity and oil/water ratio away from boreholes.
B.	Need/ significance:	To evaluate and engineer enhanced recovery operations as well as primary and secondary operations, it is very important to know the porosity and the oil-water ratio in the reservoir. Especially important is that these be known away from the boreholes, in which they may be affected by drilling fluid penetrating the formation or other effects of the drilling.
C.	Present techniques:	Electrical logs using wide spacings are employed. However, there is considerable debate about the proper interpretation of such data.
D.	Matching aerospace technology:	Remote sensing. Instrumentation. Acoustic tomography.
E.	Concepts for consideration:	Acoustic tomography. Sidewall drilling with sampling and measurements between two side holes.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7.

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F1c DETERMINING RESERVOIR CHARACTERISTICS

A.	Problem:	Methods of determining overall reservoir characteristics including existence of fractures, faults, zones of high or low porosity or permeability, buried sandbars, stream beds, reefs, rock inhomogeneities, gas, oil and water quantities and interfaces.
B.	Need/ significance:	For proper evaluation of a reservoir for primary production or enhanced recovery operations, an adequate description of the entire reservoir is needed. Information on characteristics between the wells, not just at the wells, is needed.
C.	Present techniques:	(1) Tracer flow tests, both single well and well-to-well tests. (2) Pressure transient tests measuring interactions from well to well. (3) Production history of the field showing pressure decay, fluids produced. (4) Logging and coring of wells.
D.	Matching aerospace technology:	Computer modeling. Instrumentation. Remote sensing. Acoustic tomography.
E.	Concepts for consideration:	Downhole acoustic tomography. Time delay spectrometry. Reflection seismic survey from surface using extremely close detection spacing and high resolution techniques.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	High to moderate.
I.	Years until demonstration:	5-7.

F1d CHEAPER TRACER TECHNIQUE FOR WELL-TO-WELL FLOW CHARACTERISTICS

A.	Problem:	A cheaper tracer technique for determining well-to-well flow characteristics of a reservoir.
B.	Need/ significance:	One of the best methods in use for determining the permeability inhomogeneities and other flow characteristics of a reservoir between wells is to inject suitable tracers into one well and measure the rate at which they are recovered from nearby producing wells. However, the analytical techniques used to determine the tracer content in the produced fluids are relatively expensive. Chemical or chromatographic separations are usually required, following by counting adequate to separate the various activities. Also, the safety procedures necessary in using radioactive isotopes and subsequent long-term monitoring are expensive.
C.	Present techniques:	Separation and radiochemical counting.
D.	Matching aerospace technology:	Instrumentation. Radiochemistry.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

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F1e OUTLINING RESERVOIRS

A.	Problem:	Outlining reservoirs accurately without extensive drilling.
B.	Need/ significance:	For both primary and enhanced recovery, it is important to outline the horizontal extent of a reservoir. A method of doing this accurately at low cost is needed. Seismic surveys determine existence of structures but only drilling can prove that a reservoir contains oil or gas. Drilling is continued until the limits of the oil or gas production are defined. This involves the drilling of several dry holes around the perimeter of the reservoir, which is very expensive.
C.	Present techniques:	Drilling. Work is underway on such techniques as active and passive magnetotellurics, self potential, radiation halos, soil content of adsorbed organic gases, to define the extent of the reservoir.
D.	Matching aero-space technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

F1f DETERMINING VERTICAL PERMEABILITY CHARACTERISTICS

A.	Problem:	Better methods of determining the vertical flow characteristics of the reservoir.
B.	Need/ significance:	In enhanced recovery operations, the vertical permeability of the reservoir, and its variation across the bed are generally important.
C.	Present techniques:	Several methods are described in the literature.
D.	Matching aerospace technology:	Remote sensing. Instrumentation.
E.	Concepts for consideration:	Sidewall drilling with flow measurements between two side holes.
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-7

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F1g DETERMINING CONTINUOUS PHASE IN RESERVOIR

A.	Problem:	Determining which is the continuous fluid phase in a reservoir.
B.	Need/ significance:	The flow characteristics and the fraction of fluid that is extracted from a reservoir depend on which fluid is continuous: oil, gas, or water. For example, in a gas reservoir, if the gas is the continuous phase, the rate of flow through the pores will be governed by the viscosity of the gas; if the water is the continuous phase, the flow rate will be governed by the viscosity of the water, and will be much lower. For proper reservoir engineering, the identify of the continuous phase should be known. The continuous phase may change as the reservoir is produced.
C.	Present techniques:	Logging. Coring. Pressure testing. Tracers. Production history.
D.	Matching aerospace technology:	Remote measurements. Instrumentation.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	5-10.

F2a IMPROVED NUMERICAL MODELING OF RESERVOIRS

A.	Problem:	Certain reservoir processes have solutions difficult to approximate and are not yet generally susceptible to treatment by available numerical procedures. Many processes involved require such high definition in terms of reservoir heterogeneity and fluid components as to require impractical computer costs.
B.	Need/ significance:	Accurate numerical modeling of reservoirs is required for most efficient application of primary and enhanced recovery techniques, to recover more oil and gas at less cost. Particularly with gas injection, gravitational segregation should be taken into account.
C.	Present techniques:	Finite difference analysis method applied to solve these problems. Numerical dispersion is a difficulty.
D.	Matching aerospace technology:	Computer modeling. Finite element methods. NASTRAN.
E.	Concepts for consideration:	Mathematical inversion solutions utilizing production data.
F.	Importance to industry:	Low to moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low to moderate.
I.	Years until demonstration:	2-3 (using depleted reservoir data).

F2b MODEL FOR IN SITU COMBUSTION

A.	Problem:	Improved model for enhanced recovery utilizing in situ combustion.
B.	Need/ significance:	In situ combustion is an accepted enhanced recovery technique. To properly engineer such a recovery, a computer model of the reservoir with the injection and combustion processes is needed. Present models do not realistically model the kinetics of combustion but rather make certain arbitrary assumptions as to the kinetics. A better model would result if the kinetics of combustion were properly included. Preferably, gravitational segregation should also be modelled.
C.	Present techniques:	(see above)
D.	Matching aerospace technology:	Combustion chemistry and kinetics. Heat transfer. Computer modeling.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	5

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F2c CALCULATING THE REQUIRED SLUG SIZE FOR MICELLAR FLOODING

A.	Problem:	How to calculate the minimum slug size needed for micellar flooding.
B.	Need/ significance:	Considerable work is underway on micellar flooding as a method of enhanced recovery. Mixing and other losses of the injected slug play an important part in determining the cost and effectiveness of the process. Losses occur through hydrodynamic mixing with reservoir fluids, through gross heterogeneity of flow, through adsorption, etc. Better computer simulation is needed to permit better engineering of the process. If the slug is too small, it will be dissipated too early; if it is too large, a considerable amount of money is wasted.
C.	Present techniques:	Finite difference method: This is not sufficiently accurate for small slugs. Variational method: This is being tried.
D.	Matching aero-space technology:	Computer modeling. Finite element methods.
E.	Concepts for consideration:	Mathematical inversion solutions, using production and test hole data.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low to moderate.
I.	Years until demonstration:	5-10.

G1a CONTROL OF VISCOSITY OF INJECTED AND GENERATED LIQUIDS AND GASES

A.	Problem:	Increasing the viscosity of injected liquids and gases to improve conformance.
B.	Need/ significance:	Good conformance is essential for good sweep efficiency and high recovery in enhanced oil recovery operations. If the injected or generated fluid is lower in viscosity and therefore higher in mobility than the oil in the reservoir, conformance is likely to be low. Techniques for increasing the viscosity of the injected or generated fluids are therefore needed.
C.	Present techniques:	For water injection, polymers are sometimes used. For micellar flooding, polymers are usually used. For air, steam, CO_2, inert gas, or natural gas injection, and for gases produced by in-situ combustion, viscosity control agents are not ordinarily used. Injection of water, alternating with the gas phase or entrained in the steam, is used to reduce the effective mobility of the injected fluid. Use of gas-liquid emulsions has also be suggested. For miscible liquids, no technique in use.
D.	Matching aero-space technology:	Polymer chemistry and engineering. Liquid propellant engineering. Coal technology.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate to low.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5

G1b STABILITY OF POLYMER SOLUTIONS

A.	Problem:	Making polymer solutions for mobility control that are more stable to shear, high temperatures, and high salinity of reservoir fluids.
B.	Need/ significance:	Polyacrylamides and polysaccharides are the most commonly used mobility control agents in enhanced oil recovery. Polyacrylamides are stable to 200-250°F, but are readily shear degradable. Shear degradation in injection well casing perforations and fine capillaries of reservoir formation reduce mobility control of polyacrylamides and cause loss of expensive polymer material. Polysaccharides are biopolymers that are shear stable and can tolerate relatively high salinities but are unstable above 150°F. Reservoir temperatures are often above 200°F. Thermal degradation of the polymers leads to loss of mobility control and expensive materials. Moreover, polysaccharides tend to contain dead bacteria which can plug the formulation and reduce oil recovery.
C.	Present techniques:	Use of polymer systems that are known not to be degraded at the specific reservoir conditions. Diatomaceous earth filters are used to prevent dead bacteria from entering the reservoir. These filters add significantly to the cost.
D.	Matching aerospace technology:	Polymer chemistry.
E.	Concepts for consideration:	Dextrin-grafted polymers.
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5.

G1c POLYMER ADSORPTION ON RESERVOIR ROCK

A.	Problem:	Polymer solutions, used for mobility control in enhanced oil recovery, are adsorbed on reservoir rock.
B.	Need/ significance:	Adsorption of polymers in the reservoir necessitates use of more polymer which adds to the cost of enhanced oil recovery. Moreover, adsorption in pore openings can make the pores inaccessible for oil recovery and thus reduce the efficiency of enhanced oil recovery. A polymer system that is less susceptible to adsorption is needed to reduce the costs of mobility control and increase efficiency of oil recovery.
C.	Present technique:	Addition of higher amounts of polymers with broad molecular weight distribution.
D.	Matching aero-space technology:	Polymer chemistry.
E.	Concepts for consideration:	Copolymer with modified polyacrylamide to reduce adsorption.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5.

G1d COST OF POLYMERS

A.	Problem:	Costs of polymers used for mobility control in enhanced oil recovery are moderately high.
B.	Need/ significance:	In enhanced recovery techniques using mobility control, the amount and cost of the polymers are significant in the total cost of production. Cheaper polymers will reduce the cost of enhanced oil recovery and make it economically more attractive.
C.	Present techniques:	Polyacrylamides and polysaccharides.
D.	Matching aero-space technology:	Polymer chemistry.
E.	Concepts for consideration:	Dextrain-grafted polymers.
F.	Importance to industry:	High.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	Indeterminate.

G1e MEASUREMENT OF POLYMER CONCENTRATION IN RESERVOIR FLUID

A.	Problem:	No good field methods exist for measurements of polymer concentrations in the range of 5 PPm.
B.	Need/ significance:	Polymer concentrations in the reservoir are low. Better measurement would permit reducing the amount used and increase cost-effectiveness.
C.	Present techniques:	None.
D.	Matching aero-space technology:	Instrumentation. Polymer Chemistry.
E.	Concepts for consideration:	Concentration by higher pressure membrane ultra-filtration, then analysis.
F.	Importance to industry:	Moderate to low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate to high.
I.	Years until demonstration:	1-2.

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G1f PREFLUSH CONFORMANCE

A.	Problem:	Limited conformance of pre-flushing in removing saline fluid for enhanced recovery of micellar-polymer flooding.
B.	Need/ significance:	Considerable work is underway on micellar-polymer flooding as a means of enhanced recovery. At present, micellar-polymer systems are limited in the salinity at which they can operate. Accordingly, in many reservoirs, where the salinity is too high for present systems, it is necessary to first lower the salinity by pre-flushing with low salinity water. However, because the pre-flush water has low viscosity and the chemical polymer flood has high viscosity, they do not necessarily follow similar paths in the reservoir. Thus, the efficiency of pre-flush is not as good as desired.
C.	Present techniques:	Use a large volume of pre-flush.
D.	Matching aerospace technology:	Polymer chemistry and engineering.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	5-10.

G1g HANDLING HIGH POUR POINT OIL

A.	Problem:	Some oil found in Utah and elsewhere can be effectively "solid" at temperatures which occur in the bore.
B.	Need/ significance:	Solidification of high pour point oil in the well bore is a difficult problem to handle. Method needs to be developed to continuously produce this oil.
C.	Present techniques:	Dilution with solvents. Heating the well by steam, using double-walled tubing, or electrically, using wound electrical tape.
D.	Matching aero-space technology:	Radio-isotope heaters.
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low to moderate.
I.	Years until demonstration:	

G2a STABILITY OF SURFACTANT SOLUTIONS

A.	Problem:	Loss of effectiveness of surfactant solutions due to high-temperature instability, reaction with divalent ions and high salinity of reservoir fluids.
B.	Need/ significance:	Surfactant solutions (petroleum sulfonates) are used to decrease the oil-water interfacial tension to very low levels (0.001 dynes/cm) to produce micellar slugs that can displace oil efficiently. The need for surfactants that are thermally stable at 200°F or above, inert to the divalent ions and effective in high-saline conditions is dictated by both economic and efficiency considerations. The stability of surfactant solutions is one of the biggest problems.
C.	Present techniques:	Tailoring surfactants to specific reservoir temperatures, sequesterants to neutralize divalent ions, and pre-flushing to reduce reservoir salinity.
D.	Matching aero-space technology:	Non-ionic surfactants.
E.	Concepts for consideration:	Conversion of petroleum sulfonates to non-ionic by adding polyether blocks.
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	High to moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

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G2b ADSORPTION OF SURFACTANTS

A.	Problem:	Losses of petroleum sulfonates, the most commonly used surfactants in enhanced oil recovery, by adsorption on reservoir rock increases the costs and decreases efficiency.
B.	Need/ significance:	Considerable effort is underway on micellar flooding and low-tension flooding as techniques for enhanced oil recovery. Petroleum sulfonates are the generally used surfactants. Adsorption of surfactants on reservoir rock has two adverse effects; (1) direct loss of expensive chemicals and (2) alteration of molecular weight distribution of surfactants. The maintenance of optimum molecular weight distribution is critical for effectiveness of surfactants. Understanding the kinetics of adsorption and development of methods to decrease adsorption or finding alternate surfactants that do not adsorb is needed to improve cost effectiveness and efficiency of surfactants in enhanced oil recovery.
C.	Present techniques:	Use of wide molecular weight distribution of surfactants, with excess of the particular molecular weight compounds that are selectively adsorbed. Control of pH in some cases seem to reduce adsorption.
D.	Matching aerospace technology:	Non-ionic surfactants.
E.	Concepts for consideration:	Conversion of petroleum sulfonates to non-ionic.
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

G2c COST-EFFECTIVE SURFACTANTS

A.	Problem:	The high cost of petroleum sulfonates, now generally used as surfactants, make micellar flooding enhanced oil recovery methods uneconomical.
B.	Need/ significance:	Petroleum sulfonates used for micellar flooding contribute considerably to the cost of surfactant solutions and micellar slugs. The petroleum sulfonates are made by sulfonation of crude oil from the reservoir or commercially from petro-chemical feed stocks. Cheaper surfactants that are not adversely affected by fluid-fluid or fluid-rock interactions in the reservoir would improve the economics of enhanced oil recovery.
C.	Present technique:	Petroleum sulfonates.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	Waste pyrolysis.
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

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G3a CONTROL OF EFFECTIVE DENSITY OF INJECTED AND GENERATED GASES

A.	Problem:	Increasing the effective density of injected or generated gases to increase conformance.
B.	Need/ significance:	In enhanced oil recovery techniques that utilize gas injection, gravitational bypassing is of major economic importance. The gas, injected or generated in situ, tends to rise to the top of the producing formation and bypass much of the oil. This is important with steam and CO_2 injection and with in situ combustion. Techniques that would increase the effective density of the gas could be helpful.
C.	Present techniques:	Injection of water, alternating with the gas phase or entrained in the steam, is utilized to increase the effective density of the injected fluid. Use of gas-liquid emulsions has also been suggested.
D.	Matching aerospace technology:	Coal technology.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	5-10.

G4a PERMEABILITY INHOMOGENEITY

A.	Problem:	Equalizing and modifying the relative permeabilities of different portions of a reservoir.
B.	Need/ significance:	In enhanced recovery, sweep efficiency is of major economic importance, as it determines the amount of petroleum recovered. For good sweep efficiency it is important to control preferential flow of injected fluid through high permeability streaks or fractures, where it bypasses much of the oil. Techniques for equalizing and selectively adjusting the permeability of portions of the reservoir are needed. The techniques should be applicable to control not only high permeability regions at the injection well, but also high permeability regions downstream. In most cases, techniques that permit increasing permeability would be preferable to those that only decrease permeability, since the latter restrict the production rate. The detrimental effects of permeability inhomogeneity are exacerbated by low viscosity (high mobility) of the injected fluid.
C.	Present techniques:	Injection of agents that tend to flow through and selectively plug high permeability regions. One formulation uses a polyacylamide pre-polymer plus chromium ions to produce polymerization in the reservoir and plug the more permeable zones. This apparently is less workable when the high permeability zone is not adjacent to the injection well.
D.	Matching aerospace technology:	Polymer chemistry.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	5-10.

G4b CONTROL OF GRAVITATIONAL SEGREGATION BY PERMEABILITY MODIFICATION

A.	Problem:	Reducing gravitational bypassing by injected or generated gas through selective modification of permeability.
B.	Need/ significance:	In enhanced oil recovery techniques that utilize gas injection, gravitational bypassing is of major economic importance. The gas, injected or generated in situ, tends to rise to the top of the producing formation and bypass much of the oil. This is important with steam and CO_2 injection and with in situ combustion. Once the injected gas reaches the production well, a swept path essentially "clean" of oil will be present between injection and production wells; further injections will tend even more strongly to go through this path, by-passing the remaining oil. It is highly desirable to block off such a hole-to-hole swept path. Techniques that would decrease vertical permeability and flow, or that would decrease horizontal permeability at the top of the formation and/or increase it lower in the formation, could be very helpful. The low viscosity and corresponding high mobility of the gases relative to that of the oil exacerbates the difficulties.
C.	Present techniques:	No techniques based on permeability modification.
D.	Matching aerospace technology:	Propellant technology.
E.	Concepts for consideration:	
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	5.

G4c CHEMICAL PLUGGING DURING THERMAL RECOVERY

A.	Problem:	Steam and other thermal recovery processes for heavy residual oil aromatize asphaltenes into carbene which causes plugging in the reservoir and other problems. Paraffins also may cause plugging.
B.	Need/ significance:	
C.	Present techniques:	Solvents. Scraping. Emulsification has been suggested.
D.	Matching aero-space technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

G5a DE-EMULSIFICATION OF PRODUCED FLUIDS

A.	Problem:	Breaking of the oil-water emulsions produced in enhanced oil recovery opeations.
B.	Need significance:	Oil-water emulsions are produced in enhanced oil recovery methods or deliberately introduced as in micellar flooding. These emulsions are hard to break up and decrease the value of produced crude. De-emulsification is necessary to remove the water from the crude.
C.	Present technique:	Design of specific de-emulsification procedures for specific situations.
D.	Matching aerospace technology:	Chemical propellent processing.
E.	Concepts for consideration:	Enhance separation by opposing vertical surfaces; one being hydrophillic and the other hydrophobic.
F.	Importance to industry:	Low to moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years to demonstration:	2.

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G6a TREATING PRODUCED WATER

A.	Problem:	Large amounts of water that are produced along with oil in many enhanced recovery operations have high sulfur or salt content.
B.	Need/ significance:	It is mandatory to meet EPA standards for water discharge into natural water bodies, groundwater, or municipal sewers. Therefore, if the produced water cannot be re-used in the enhanced oil recovery processes, it has to be treated for the removal of its sulfur and salt contents. An economical method is necessary to treat the produced water so that it will not add significantly to the costs of enhanced oil recovery.
C.	Present techniques:	Re-injection of produced water. Some treatment methods are in use, on offshore platforms and on land.
D.	Matching aero-space technology:	
E.	Concepts for consideration:	Semipermeable membranes.
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace constribution:	Moderate.
I.	Years until demonstration:	2.

G6b WATER SUPPLY FOR STEAM INJECTION

A.	Problem:	Providing enough suitable water for steam injection.
B.	Need/ significance:	Steam injection is a proven method of enhancing oil recovery, especially for very heavy crudes. Large quantities of water are needed from which to make the steam. The water quality must be adequate to avoid excessive scaling in the steam generators. Available water supplies are often limited or brackish.
C.	Present techniques:	Generally, available fresh water is used, with pretreatment as is usual for boiler feed water.
D.	Matching aerospace technology:	Power Plants. Desalinization of sea water, especially by waste heat.
E.	Concepts for consideration:	Semipermeable membranes. Waste heat distillation.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	2-3

G6c REUSE OF PRODUCED WATER

A.	Problem:	The high salinity, high divalent ion concentration and oxygen carried from the surface make it difficult to reuse produced water for enhanced oil recovery operation.
B.	Need/ significance:	Steam generation is one use for the produced water. The high salinity of produced water make it unusable with conventional steam generators. Treating the water to reduce the salinity or development of a steam generator that can handle high salinity water is needed. The produced water can also be used as drive fluid in surfactant and micellar flooding operation. The high salinity, high concentration of divalent ions and oxygen carried from the surface in the produced water makes it incompatible for use in surfactant and micellar flooding: it produces precipitates which clog the formations. Treating the water to reduce salinity and concentration of divalent ions can make it suitable for reuse in enhanced recovery operations. The reuse of produced water will not only improve the economics but also eliminate the problem of disposing of the water.
C.	Present technique:	Single pass tube type steam generators using fairly pure water are generally used. Produced water is disposed of down special wells or treated to make it suitable for reinjection.
D.	Matching aerospace technology:	Desalinization of sea water, especially by waste heat. Treatment of cooling tower water.
E.	Concepts for consideration:	Semipermeable membranes. Waste heat distillation.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Moderate.
I.	Years until demonstration:	2-3

H1a CARBON DIOXIDE PRODUCTION

A.	Problem:	Additional, inexpensive, supplies of CO_2 in the field are needed.
B.	Need/ significance:	Additional supplies and reduced costs would result in increased usage of this effective, enhanced recovery technique.
C.	Present techniques:	CO_2 is produced from natural wells and transported by pipeline or trucks to the oil fields. Separation from stack gases in cracking or ammonia plants has been suggested as another approach. Produced CO_2 must be free from contaminants such as N_2 which decrease miscibility with oil and must be compressed to above oil reservoir pressure.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

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H1b SEPARATION OF CO_2 FROM PRODUCED GASES

A.	Problem:	Economic separation of CO_2 from hydrocarbons produced during CO_2 flooding.
B.	Need/ significance:	In order to sell the light hydrocarbons such as CH_4 and/or reinject the CO_2 a separation must be made which is not at present economical.
C.	Present techniques:	Separate by scrubbing.
D.	Matching aero-space technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Low to moderate.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

H2a GAS COMPRESSION

A.	Problem:	The costs of compressing CO_2 for CO_2 flooding, air for in situ burning, and natural gas for reinjection need to be reduced.
B.	Need/ significance:	The present cost of compressing air is in the $300/hp-range; above 600 psi it may be higher. The problem is common to several enhanced recovery techniques. Very large volumes of compressed air are needed. Lubrication and explosions are problems, as is maintenance of the equipment.
C.	Present techniques:	Turbines and reciprocal compressors used; latter particularly require maintenance.
D.	Matching aero-space technology:	High capacity reliable pump technology.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	Low to moderate.
I.	Years until demonstration:	

H3a HEAT LOSSES IN STEAM INJECTION

A.	Problem:	The steam injection technique loses efficiency with increasing depth because of heat losses along the injection well.
B.	Need/ significance:	Heat losses of 5 to 15%/1000 ft of depth increase the cost of this technique. Reduction of heat loss would make the technique economical in mine fields.
C.	Present techniques:	Casing insulation such as sodium silicate and the use of down-hole heaters have been suggested.
D.	Matching aero-space technology:	Insulating and temperature control experience from cryogenic technology, rocket propulsion and temperature control of spacecraft.
E.	Concepts for consideration:	Double pipe technique with air insulation and convection blocks.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	2-3

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H3b DOWNHOLE GENERATION OF HEAT FOR ENHANCED RECOVERY

A.	Problem:	The means of generating heat downhole is needed for enhanced recovery by steam flooding.
B.	Need/ significance:	Thermal stresses along the injection well limit the depth at which steam flooding can be used effectively. If the steam could be produced by providing the heat at the bottom of the well, this depth limitation would be removed and steam flooding could be much more widely used.
C.	Present techniques:	Burn fuel at the surface to produce steam which is piped down the injection well.
D.	Matching aerospace technology:	Rocket propulsion. Radioactive thermal sources.
E.	Concepts for consideration:	Heating water downhole with a capsule of highly radioactive waste (probably not practical).
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

H3c STEAM GENERATION FROM LOW-QUALITY WATER

A.	Problem:	A steam generator is needed which is capable of operating on produced water or other available impure water without purification.
B.	Need/ significance:	The application of steam flooding is limited in some localities by the need to purify the supply water. This may make the technique uneconomical.
C.	Present techniques:	Fresh water of good purity is usually used, with minimal pretreatment. For brackish water, heat transfer via molten salt is sometimes used.
D.	Matching aerospace technology:	Power plants. Materials engineering. Ultrasonics. Electrostatics.
E.	Concepts for consideration:	Use scale-resistant materials or disposable lining materials. Direct contact heat exchangers.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	Moderate to high.
H.	Likelihood of significant aerospace contribution:	Moderate to low.
I.	Years until demonstration:	5

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H3d LOW COST STEAM

A.	Problem:	Cost of generating steam for flooding.
B.	Need/ significance:	The cost of the steam is a major component of the overall cost of enhanced recovery by steam injection.
C.	Present techniques:	Steam has usually been produced in steam generators using as a fuel available natural gas or crude produced from the field. Gas is not always available and its value for other purposes is rising, relative to that of oil. Often, so much gas or crude would have to be burnt to produce steam that the method is uneconomic. Many of the crudes of interest for steam flooding are high in sulfur; if they are burnt to raise steam, steps must be taken to avoid releasing SO_2 into the environment. This adds to the cost. Coal heating has been suggested.
D.	Matching aero-space technology:	Propulsion/combustion engineering. Energy technology. Solar energy. Radio-isotope heaters.
E.	Concepts for consideration:	Solar heating (appears too expensive).
F.	Importance to industry:	High.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low.
I.	Years until demonstration:	

IIa DETAILED MAPPING OF SEA BOTTOM

A.	Problem:	Obtaining large-scale maps of selected areas of sea bottom.
B.	Need/ significance:	For siting and designing drilling platforms, pipelines, and other structures, detailed knowledge of the local sea bottom topography and character is needed. Available charts of off-shore areas typically have vertical and horizontal resolutions 2 orders of magnitude poorer than that needed.
C.	Present techniques:	Echo-sounding: this gives coverage only along a line, rather than over an area. Surveys along a great many such lines would be needed to provide adequate coverage. Side-looking sonar: present sonar techniques provide the data as a few shades of gray on sea-sensitive paper with considerable geometric distortion. This output is difficult to understand and interpret.
D.	Matching aerospace technology:	Digital optical, radar, and sonar image processing. High-quality image display.
E.	Concepts for consideration:	Digital side-looking sonar data could be processed to remove distortions and presented as high-quality images on photographic film or paper. Echo-sounding data can be combined with the sonar data to provide depth calibration and permit computer-contouring to provide detailed topographic maps.
F.	Importance to industry:	Low.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	3.

IIb SEA-BOTTOM CHARACTERISTICS

A.	Problem:	Data on sea-bottom characteristics for various offshore localities.
B.	Need/ significance:	For design, construction, and maintenance of sea bottom facilities, such as sea floor well heads, it is necessary to know the sea-bottom characteristics likely to be encountered. In addition to local topography (problem IIa), data are needed on: the mechanical properties of the bottom to some depth; currents, temperatures, and their variations; the likelihood of turbidity currents and other disturbances; presence of hydrocarbon seeps; etc.
C.	Present techniques:	Echo sounders. Oceanographic instruments, towed or dropped. Hydrocarbon sensors. Divers.
D.	Matching aerospace technology:	Remote sensing. Measurements using unmanned vehicles. Technology of unmanned vehicles.
E.	Concepts for consideration:	Make measurements from unmanned vehicle, towed or free-swimming.
F.	Importance to industry:	Moderate.
G.	Importance to ERDA:	High.
H.	Likelihood of significant aerospace contribution:	High to moderate.
I.	Years until demonstration:	2.

IIc SEA-ICE PREDICTION

A.	Problem:	Measurement and prediction of sea ice location, thickness, strength, and pressure. Tracking and prediction of iceberg position.
B.	Need/ significance:	For operation of drilling platforms, ships, and supply in arctic waters.
C.	Present technique:	Location from ship, aircraft, shore stations. Thickness from ships. Strength occasionally from ships. Pressure sometimes estimated from wind speed and drag coefficient of upper surfaces of floes, if these are known.
D.	Matching aerospace technology	Aircraft. Satellites. Remote imaging. Imaging radar. Radiometry. Image processing.
E.	Concepts for consideration:	Aircraft and satellite imaging, imaging radar, radiometry. Location can be determined by imaging and by imaging radar. Floe motion can be tracked with radio beacons dropped from the air and communicating via satellite. Microwave radiometry can distinguish first-year ice from multi-year ice and so provide an identification of thickness and strength. Measurement of the height of floe upper surface above the sea may be possible by radar; this would also give an indication of thickness and possible strength. Imaging radar also gives an indication of structure, strength, and thickness. Providing observations with adequate resolution, area coverage and frequency may be a problem. Aircraft provide good radar and radiometry resolution but coverage may be difficult. Seasat will provide good radar resolution and adequate coverage but the microwave radiometer resolution of Seasat and Nimbus G is only about 20 km.
F.	Importance to industry:	Low since work underway.
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	High
I.	Years to demonstration:	0

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II.d OFFSHORE WEATHER PREDICTION

A.	Problem:	Better prediction of offshore weather.
B.	Need/ significance:	Offshore drilling, pipelaying, and installation of platforms and equipment are critically dependent upon the weather. If an unexpected storm strikes, lives and equipment may be lost. On the other hand, shutting down operations in anticipation of a storm that does not appear or is not severe wastes large amounts of money. For some offshore areas, observation stations in the proper locations are few or lacking and predictions are accordingly inaccurate.
C.	Present techniques:	Observations from ground stations, ships, aircraft, satellites.
D.	Matching aerospace technology:	Aircraft. Satellites. Remote instrumentation. Telecommunications. Data processing and analysis.
E.	Concepts for consideration:	More extensive use of dropped weather buoys, telemetering data via satellite. Improved methods of interpreting and using weather satellite data.
F.	Importance to industry:	High.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	3-5

IIe EARTHQUAKE PREDICTION

A.	Problem:	Prediction of location and magnitude of earthquake ground motion.
B.	Need/ significance:	To help in location and design of offshore platforms and other structures.
C.	Present techniques:	None operational in U.S.A. Operational in China on-land, using techniques listed below plus behavior of water wells and animals.
D.	Matching aerospace technology:	Radio astronomy. Data analysis and processing. Data platforms transmitting via satellite.
E.	Concepts for consideration:	Considerable international effort underway. Present approaches: monitoring of changes in seismic wave velocities, measurements of crustal strain and displacement by long baseline radio interferometry and ground measurements, electrical and magnetic monitoring of changes in ground electrical resistance. In the U.S., major efforts involve the U.S.G.S., universities and NASA laboratories.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	High
I.	Years until demonstration:	Indeterminate

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I2a OFFSHORE PLATFORM DESIGN

A.	Problem:	Design of offshore platforms for minimum cost and adequate safety.
B.	Need/ significance:	Offshore platforms are extremely expensive. If they are overdesigned, large amounts of money are wasted. If they are underdesigned, very expensive failures may occur.
C.	Present techniques:	Considerable work has been done and is underway on platform design. Present designs are conventional. The techniques used are those of civil engineering.
D.	Matching aerospace technology:	Engineering design. Physical and mathematical modeling and testing. Remotely controlled operations.
E.	Concepts for consideration:	Structural design, modeling, and tests procedures as used in aerospace engineering may lead to more reliable and less costly platform designs.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	20

I2b MARINE DRILLING IN STORMS

A.	Problem:	Marine drilling interruptions by storms.
B.	Need/ significance:	Marine drilling operations in some areas are often interrupted by storms. These interruptions are very costly.
C.	Present techniques:	When severe storm is expected, interrupt drilling, secure equipment, seek shelter for personnel.
D.	Matching aerospace technology:	Satellite sea sensing and weather sensing. Mechanical engineering. Remotely controlled operations. Robotics.
E.	Concepts for consideration:	Automated rigs.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate.
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

I2c ICEBERG CONTROL

A.	Problem:	Diversion or destruction of approaching icebergs that threaten a drilling or production platform.
B.	Need/ significance:	Large icebergs are a threat to drilling and production equipment in arctic waters.
C.	Present technique:	Keep tugs on standby; use them to divert threatening bergs. This is expensive.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

I2d INSPECTION AND MANIPULATION OF EQUIPMENT ON SEA BOTTOM

A.	Problem:	Inspection and manipulation of well head equipment on sea bottom.
B.	Need/ significance:	There are significant advantages in completing offshore wells at the sea bottom, instead of on platforms above the sea. Better techniques are needed to permit inspection and manipulation of well head equipment as needed for operation and maintenance.
C.	Present techniques:	Divers. Small manned submersibles. Unmanned cameras and manipulators. Pressurized room around well heads.
D.	Matching aerospace technology:	Remote manipulation, sensing and imaging. Robotics. Manned and unmanned submersibles and towed undersea vehicles.
E.	Concepts for consideration:	An aerospace company is developing a 1-atmosphere room. Unmanned submersibles with imaging and manipulators.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	High to moderate
I.	Years until demonstration:	3-5

I2e SEA-ICE HAZARD TO COMPLETED WELLS

A.	Problem:	How to complete and maintain wells offshore in areas where floating ice scrapes the bottom.
B.	Need/ significance:	In some offshore Arctic areas, floating ice is a major hazard. How can wells be completed when the ice scrapes the bottom and is likely to destroy any equipment extending above the bottom? How can maintenance be carried out under such conditions? Humans must be protected both from the ice and water and from hydrocarbons and other emissions that may come from the well.
C.	Present techniques:	Consideration is being given to building rooms below the ocean bottom, in which the men may work. The problem of providing a satisfactory atmosphere in these rooms is not yet solved, nor is it clear that the subfloor rooms are the best solution.
D.	Matching aerospace technology:	Life support. Mechanical engineering. Escape devices.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

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I2f BRINGING OIL TO SURFACE AND SHORE IN ARCTIC SEAS

A.	Problem:	Bringing oil to surface of icy seas and to shore.
B.	Need/ significance:	Large amounts of oil are believed to lie offshore in arctic areas. There are severe difficulties in bringing the oil from the sea bottom to the surface and storing or shipping it. Fixed or floating platforms may be damaged or destroyed by heavy ice or bergs. The risers may also be damaged or destroyed. Once the oil reaches the sea surface, it is hard to ship it out across an icy or frozen sea, and hard to store it safely. If a sea-bottom pipeline is built from the wells to shore, floating ice may scour the bottom and destroy the pipeline.
C.	Present techniques:	As above.
D.	Matching aerospace technology:	Mechanical engineering. Transmission of energy by microwave
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate
H.	Likelihood of significance aerospace contribution:	Low
I.	Years until demonstration:	

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I2g PERMAFROST

A.	Problem:	Operations in permafrost areas.
B.	Need/ significance:	In many arctic areas, there is a layer of permafrost just below the land surface. If this layer is not maintained, the resulting subsurface water will impair the integrity of buildings, other structures, roads, pipelines, etc. The problem is especially severe for pipelines and storage facilities containing hot fluids.
C.	Present techniques:	Careful design to maintain the permafrost.
D.	Matching aerospace technology:	Temperature control.
E.	Concepts for consideration:	Heat pipes are being tried along the Alaska pipeline.
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate to high
I.	Years until demonstration:	0

I2h COPING WITH LOW ARCTIC TEMPERATURES

A.	Problem:	Coping with low temperature conditions in the arctic.
B.	Need/ significance:	The low temperatures often encountered in the arctic pose severe problems for people, materials, and equipment. Better ways of coping with these problems are needed.
C.	Present techniques:	
D.	Matching aerospace technology:	Selection and testing of materials for low temperature service. Design of equipment for low temperature service. Temperature control.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Moderate to high
I.	Years until demonstration:	Indeterminate

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I2j SCHEDULING ARCTIC LOGISTICS

A.	Problem:	Scheduling of arctic logistics.
B.	Need/ significance:	Logistics in the arctic are critically dependent upon season and weather. Economic movement of equipment, materials, and people are possible only when these conditions are favorable. The resulting scheduling problem is very difficult.
C.	Present techniques:	Utilize available climatologic and meteorological information as a basis for scheduling.
D.	Matching aerospace technology:	Aircraft. Satellites. Systems engineering.
E.	Concepts for consideration:	
F.	Importance to industry:	Low
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	Indeterminate

I2k DEEPWATER PRODUCTION

A.	Problem:	Currently, it is not generally economically feasible to produce oil in water deeper than 1,000 ft.
B.	Need/ significance:	There is no reason to think that petroleum deposits are limited to land and to shallow ocean depths (1000 ft). Considerable additional petroleum should be recoverable if techniques were available to produce economically through greater water depths. One difficulty is in getting the petroleum to the surface and to shore cheaply.
C.	Present techniques:	Ship platforms, semi-submersible platforms.
D.	Matching aerospace technology:	Mechanical engineering. Remote manipulation. Robotics.
E.	Concepts for consideration:	
F.	Importance to industry:	Low to moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	5-10

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I21 ARCTIC OFFSHORE COMMUNICATION

A.	Problem:	Maintaining communications to and from ships, platforms, and other offshore equipment in the arctic.
B.	Need/ significance:	Communications difficulties may arise on account of magnetic storms, aurorae, and weather conditions. This may interfere with operations and may jeopardize safety.
C.	Present techniques:	Marine radio. Macrowave if in line-of-sight of a shore installation.
D.	Matching aerospace technology:	Telecommunications. Satellites.
E.	Concepts for consideration:	Marisat covers some arctic areas. Marine communications satellites with better arctic coverage.
F.	Importance to industry:	Low.
G.	Importance to ERDA:	Low.
H.	Likelihood of significant aerospace contribution:	High.
I.	Years until demonstration:	0

J1a FLUE GAS EMISSIONS

A.	Problem:	Both in situ combustion and steam generation for steam flooding, using high sulfur lease crude oil as fuel, produce flue gases that cause unacceptable atmospheric pollution from such components as sulfur dioxide and particulates.
B.	Need/ significance:	It is necessary to meet EPA standards for flue gas emissions to obtain permits for steam generation and in-situ combustion. The present flue gas scrubbing technology is expensive and adds significantly to cost of enhanced oil recovery. Some enhanced oil recovery projects may have to be abandoned if an economical method to treat flue gases is not found.
C.	Present techniques:	Several flue gas scrubbing methods are being tried.
D.	Matching aerospace technology:	Combustion. Rocket propulsion.
E.	Concepts for consideration:	For steam generation: 2-stage combustion, removing sulfur after the first stage. This reduces the volume of gas to be treated. Also, the combustion is cooler so less NO_x is produced.
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	5

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J1b OIL DESULFURIZATION

A.	Problem:	Removal of sulfur from crude oil to be burned to make steam for steam flooding.
B.	Need/ significance:	Crude oil is burned to generate steam for the steam flooding process. The sulfur content of the crude oil leads to emission of sulfur dioxide into the atmosphere. It is necessary to meet EPA standards for flue gas emissions. Desulfurization of crude oil will help eliminate the need for expensive flue gas scrubbing. However, the present oil desulfurization methods are also expensive. An economical method for desulfurization of oil is therefore needed.
C.	Present techniques:	Standard desulfurization methods.
D.	Matching aerospace technology:	Bacterial chemistry.
E.	Concepts for consideration:	Bacterial treatment. Chlorinization.
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	5

J2a SYSTEMS APPROACH TO REGIONAL ENERGY NEEDS

A.	Problem:	Providing a systems approach to meeting regional energy needs.
B.	Need/ significance:	It is alleged that ERDA's overall energy planning and development in general, and its enhanced recovery efforts in particular, are compartmentalized by techniques. For example, the overall effort is divided into petroleum, coal, oilshale, nuclear, solar, geothermal, etc. The enhanced recovery effort is divided into micellar polymer flooding, CO_2 flooding, improved water flooding, thermal recovery, massive hydraulic fracturing, chemical explosive fracturing, and deviated well tests. What is needed, however, is an overall assessment of the problems of each region, choosing and combining specific enhanced petroleum recovery techniques with solar energy, nuclear, coal, or whatever. For example, it might be desirable to use solar heat or coal as a means of getting heavy oil to the surface.
C.	Present techniques:	For the most part, consideration and development of individual possible techniques or resources.
D.	Matching aerospace technology:	Systems engineering.
E.	Concepts for consideration:	Some effort is under way using a regional, systems engineering approach.
F.	Importance to industry:	Low to moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Moderate
I.	Years until demonstration:	5-10

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J2b TECHNICAL INFORMATION FOR GOVERNMENT ACTIONS

A.	Problem:	The federal government and other governmental entities need better technical information as a basis for their planning and regulatory decisions on petroleum and other energy resources.
B.	Need/ significance:	Sound, unbiased technical information is needed as a basis for governmental planning and action. The government is wary of industrial inputs and recommendations, since it feels they are not unbiased. On the other hand, the government in-house technical information is somewhat limited. A better, more effective, source of sound, unbiased technical information for the government is needed.
C.	Present techniques:	Inputs from industry and government personnel.
D.	Matching aerospace technology:	History of managing projects involving industry - government cooperation.
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate to high
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

J2c OBSTACLES TO UNITIZATION

A.	Problem:	Institutional and legal obstacles to unitization.
B.	Need/ significance:	For efficient enhanced recovery operation, the entire reservoir should be treated as a unit. However, institutional and legal factors sometimes prevent this.
C.	Present techniques:	Lease owners and operators try to negotiate an acceptable unitization plan.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

K1a FLOODING METHOD FOR ENHANCED GAS RECOVERY

A.	Problem:	Need a flooding method to enhance recovery of natural gas.
B.	Need/ significance:	Primary recovery methods for natural gas typically leave about 20% of the original gas in the reservoir, adsorbed on the rocks. A suitable flooding technique would permit recovering some of this fraction. Water is not suitable.
C.	Present techniques:	None in use. Suggested is flooding with nitrogen, if it could be obtained cheaply enough, would extract enough natural gas, and could be separated from the natural gas cheaply enough.
D.	Matching aerospace technology:	
E.	Concepts for consideration:	
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Moderate
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

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K1b NEW METHODS FOR ENHANCED RECOVERY OF OIL

A.	Problem:	New methods for enhanced recovery of oil.
B.	Need/ significance:	Present enhanced recovery techniques all have serious limitations. If a new and economical method were available, recoveries could be enhanced significantly.
C.	Present techniques:	Water flood, polymer-thickened flood, inert gas flood, steam heating and displacement, in situ combustion, solution flood with various soluble chemicals, micellar flood, combinations of these.
D.	Matching aerospace technology:	Fluid mechanics
E.	Concepts for consideration:	
F.	Importance to industry:	High
G.	Importance to ERDA:	High
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

K1c IN-SITU REFINING

A.	Problem:	Develop technique of utilizing available time, heat, pressure and large surface area underground in the reservoir to partially refine the crude before it is extracted.
B.	Need / significance:	If technique could be developed, costs and environmental impact of refining might be reduced.
C.	Present techniques:	None.
D.	Matching aerospace technology:	Biological engineering.
E.	Concepts for consideration:	Better engineering of in-situ combustion to improve quality of product.
F.	Importance to industry:	Moderate
G.	Importance to ERDA:	Low
H.	Likelihood of significant aerospace contribution:	Low
I.	Years until demonstration:	

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APPENDIX D

SOME ASPECTS OF HOLE-TO-HOLE SEISMIC TOMOGRAPHY

S. Parthasarathy

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A. TOMOGRAPHIC INVERSION

For the purpose of demonstrating the method of tomographic reconstruction, consider the ray paths of the seismic signal (Figure D-1) from P source positions S_1, S_2, ... S_P in one borehole to Q geophones G_1, G_2, ... G_Q in another borehole (or along the surface, in the same plane). There are PQ rays. For the moment these are taken as straight lines; effects of refraction, reflection, diffraction, etc., will be considered later. The two-dimensional cross section between the two boreholes is divided into a grid of rectangular regions ("picture elements" or "pixels"). Each pixel is identified on Cartesian coordinates by the indices i and j where i = 1, 2, ... M and j = 1, 2, ... N. There are a total of MN pixels and MN is generally > PQ.

Consider the "time" picture first. The measured time of travel from source S_K to geophone G_L is

$$T_{KL} = \Sigma t_{ij} \omega_{ijKL} \tag{1}$$

with

$$t_{ij} = \sqrt{\Delta X \cdot \Delta Z}\,/V_{ij} \tag{2}$$

and

$$\omega_{ijKL} = \frac{l_{ijKL}}{\sqrt{\Delta X \cdot \Delta Z}} \tag{3}$$

where

ΔX = pixel length in X direction

ΔZ = pixel length in Z direction

V_{ij} = velocity in pixel ij

l_{ijKL} = length of intercept with pixel ij of the ray from S_K to G_L

and the summation i j is carried over all pixels intercepted by the ray path. In equation (1), t_{ij} represents an (unknown) transmission time depending on the (unknown) velocity of transmission of the material in pixel ij, and ω_{ijKL} can be considered as a (known) weighting factor. Equation (1) expresses the fact that the weighted sum of the transmission time of all the pixels intercepted by the ray KL is equal to the (known) arrival time of the signal at phone G_L.

Various methods are available for obtaining the solutions of the stated simultaneous equations (Ref. D-1). Among them, the algebraic reconstruction technique (Ref. D-2), an iterative method, seems to be particularly suited to the present problem since the storage requirements for the computer are minimized and the calculations converge relatively rapidly.

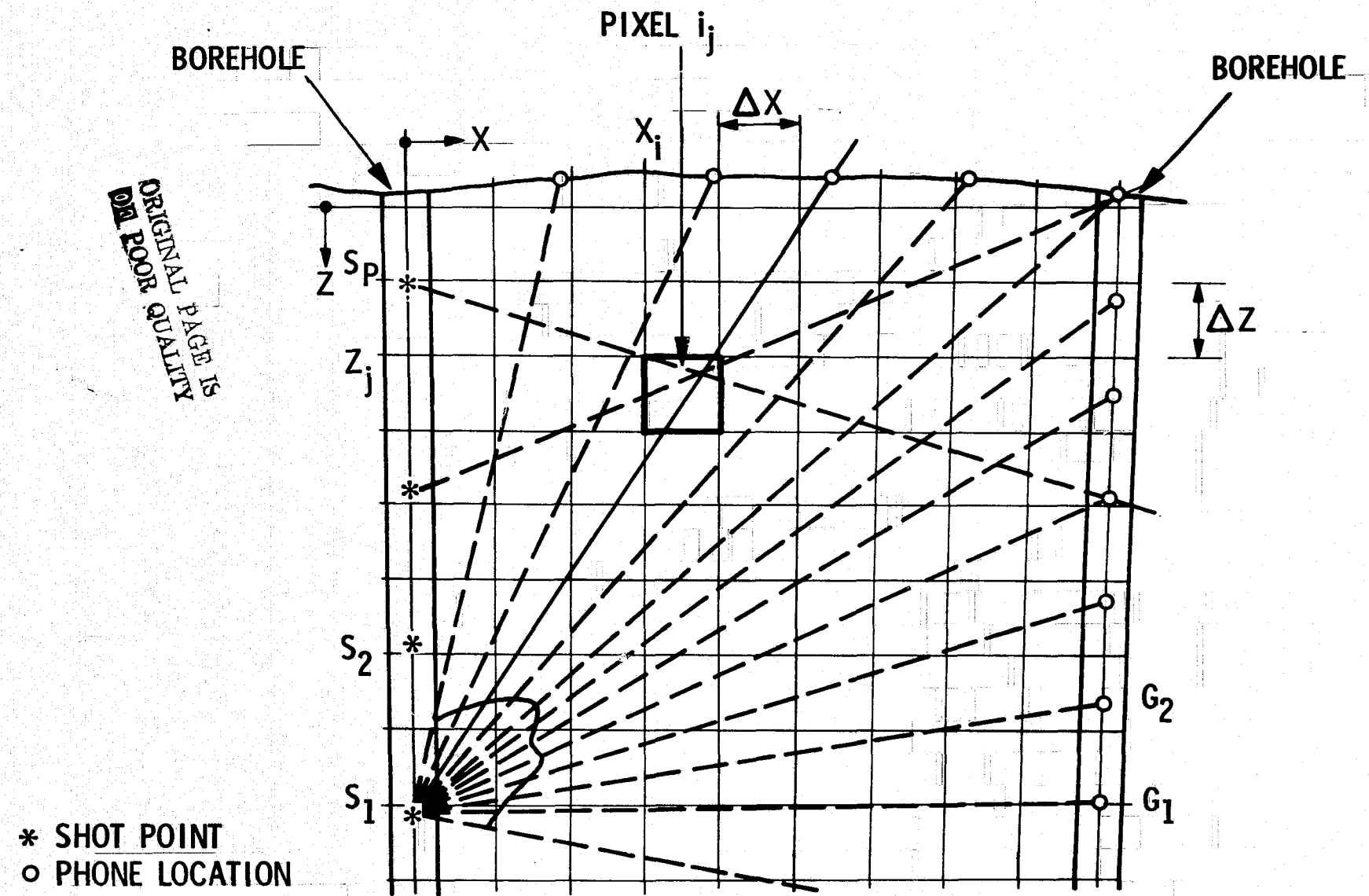

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Figure D-1. Processing for Tomographic Reconstruction

The following is one method of algebraic reconstruction using a multiplicative inversion for the first step and summations thereafter. First calculate

$$\alpha_{ij} = \prod \left(\frac{T_{KL}}{\omega_{ijKL}} \right) \tag{4}$$

where the product is taken over all rays KL that pass through the pixel ij. This is next normalized using a chosen ray K_1L_1 as reference.

i.e.,

$$t_{ij}^{(1)} = \frac{\alpha_{ij} \; T_{K_1L_1}}{\sum \alpha_{ij} \; \omega_{ijK_1L_1}} \tag{5}$$

where the sum is taken over all pixels intercepted by ray K_1L_1.

At this step, $\sum t_{ij} \, \omega_{ijK_1L_1}$ is exactly equal to the measured $T_{K_1L_1}$ and all pixels have an approximate t_{ij}. The next steps will be iterative. Starting with ray S_1G_1 the error

$$T_{11} - \sum t_{ij}^{(1)} \, \omega_{ij11}$$

is distributed uniformly along all pixels in the path S_1G_1. If N_{11} is the number of pixels along ray S_1G_1,

$$t_{ij}^{(2)} = t_{ij}^{(1)} + \frac{T_{11} - \sum t_{ij}^{(1)} \, \omega_{ij11}}{N_{11}} \tag{6}$$

Next go to S_1G_2 and repeat the process for the pixels N_{12} and so on to S_1G_Q. Continue from S_2G_1, ... to S_2G_Q, S_3G_1, ... S_PG_Q and then back to S_1G_1. The process is continued till the error

$$T_{KL} - \sum t_{ij} \; \omega_{ijKL}$$

is below a small prescribed value.

A similar procedure for the amplitudes of the transmitted waves can be followed and one can obtain an "amplitude picture" of the same cross section.

An extensive literature on algorithms and procedures for tomographic inversion is available, primarily in medical publications (See, for example, Refs. D-3 and D-4).

B. SEISMIC SOURCE STRENGTH

An estimate of how energetic a source must be for tomography will be made in the following paragraphs. The smallest measurable signal determines how big a source is needed.

Waves emitted from a small source into the rock medium lose their intensity due to spreading and absorption. We consider first the case with no absorption. We follow the derivations of Reference D-5.

A spherical cavity of radius r in an infinite elastic medium has a pressure p(t) acting inside. The solution for the wave motion is obtained by using a displacement potential of the form

$$\phi(R,t) = \frac{f\left(t - \frac{R-r}{v}\right)}{R} \tag{8}$$

with the radial displacement

$$u_R = \frac{\partial \phi}{\partial R} \tag{9}$$

Here R is distance, t is time, and v is the velocity of longitudinal waves in the medium. It can be shown that f is given by

$$f(t) = -\frac{r}{\rho\omega} e^{-\frac{\omega t}{\sqrt{2}}} \int_0^t e^{\frac{\omega\xi}{\sqrt{2}}} p(\xi) \sin \omega(t - \xi)\, d\xi \tag{10}$$

where ρ is the density and the frequency ω is given by

$$\omega = \frac{2\sqrt{2}}{3} \frac{v}{r} \tag{11}$$

In the particular case of a step change of pressure

$$p = 0 \quad \text{for } t < 0$$

$$p = p_o \quad \text{for } t \geq 0 \tag{12}$$

the solution for the displacement u_R is given by

$$u_R(R,t) = \frac{r\, p_o}{4\mu}\left[\left(\frac{r}{R}\right)^2 - \sqrt{\frac{3}{2}}\left(\frac{r}{R}\right)^2 e^{-\frac{\omega t'}{\sqrt{2}}} \sin\left(\omega t' + \tan^{-1}\sqrt{2}\right)\right.$$

$$\left. + \sqrt{2}\left(\frac{r}{R}\right) e^{-\frac{\omega t'}{\sqrt{2}}} \sin \omega t'\right] \qquad (13)$$

where t' stands for the retarded time

$$t' = t - \frac{R - r}{v} \qquad (14)$$

and μ stands for the rigidity modulus.

In the far field where $R >> r$, the terms in $(r/R)^2$ may be dropped and the substitution for ω made using (11) to yield

$$u_R(R,t) = \frac{\sqrt{2}\, r^2\, p_o}{4\mu R} e^{-\frac{2}{3}\frac{v}{r}t'} \sin \frac{2\sqrt{2}}{3}\frac{vt'}{r} \qquad (15)$$

The energy flux per unit time per unit area is given by the Poynting vector

$$\underline{W} = \underline{v}\,\rho \left(\frac{\partial u_R}{\partial t}\right)^2 \qquad (16)$$

This is a vector along the ray. The maximum value of $\underline{W}$ is at $t' = 0$ and is given by

$$\underline{W}_{max} = \underline{v}\,\frac{\rho v^2}{9}\,\frac{p_o^2}{\mu^2}\,\frac{r^2}{R^2} \qquad (17)$$

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This power flux depends on the pressure squared at the source and shows the inverse square decay with increasing R/r due to spherical spreading. Attenuation of the medium has been ignored in this solution.

Consider the following typical values for sandstone:

$$\rho = 2.2 \times 10^3 \text{ kg/m}^3$$

$$v = 3 \text{ km/s}$$

$$\mu = \rho b^2$$

where

b = shear velocity = 1.5 km/s

$$\mu = 2.2 \times 10^3 \, (1.5 \times 10^3)^2$$

$$= 4.95 \times 10^9 \text{ N/m}^2$$

The magnitude of

$$W_{max} = 2.7 \times 10^{-7} \, p_o^2 \, (r/R)^2 \qquad (18)$$

A peak pressure of 200 atmospheres due to the source explosion should be tolerable in a cased or uncased borehole (Ref. D-6). Assume the casing or borehole has a 10 cm radius. The power flux at a distance of 1 m from the center will then be

$$W_{max}(1 \text{ m}) = 2.7 \times 10^{-7} \times (101325 \times 200)^2 \times (1/10)^2$$

$$\simeq 1.1 \times 10^6 \text{ W/m}^2 \qquad (19)$$

Some additional losses will occur at the interfaces between water, casing, cement, and rock. The thicknesses of water, casing, and cement are all small compared to the wavelengths of interest; therefore, as explained below, the losses at these wavelengths will be small.

The permissible flux given by equation (19) may be compared to the flux expected from an explosive source. According to Reference D-7, detonation of 50 lb of TNT in water radiates 126×10^9 W in the shock wave. The corresponding flux at 1 m is

$$126 \times 10^9 / 4\pi = 1.0 \times 10^{10} \text{ W/m}^2$$

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Comparing this to equation (19), one finds the mass of explosive needed to produce the assumed peak pressure of 200 atm at a 10 cm radius is

$$\frac{1.1 \times 10^6}{1.0 \times 10^{10}} 50\ (454) = 2.5\ \text{g}$$

This is the amount of explosive in a few blasting caps. Experience indicates that such a change will not damage a cased hole; some experiments (Ref. D-8) suggest that charges of 24 g or more can be safely used in a cased hole.

C. SENSITIVITY OF GEOPHONES

In Reference D-9, Anstey quotes a value of 1 μV for the ambient seismic noise on the surface. Geophones clamped to the borehole walls deep with in the ground may be expected to be less noisy. If the same value of 1 μV is assumed for the ambient noise, we will get conservative estimates. Surface geophones produce a signal output of about 10 volts for a particle velocity of 1 m/s which corresponds to a power flux of magnitude

$$\rho V(1)^2 = 2.2 \times 10^3 \times 3 \times 10^3 \times (1)^2 = 6.6 \times 10^6\ \text{W/m}^2$$

A signal of 1μV therefore corresponds to the power flux

$$W_{amb} = 6.6 \times 10^6 \times (10^{-6}/10)^2 = 6.6 \times 10^{-8}\ \text{W/m}^2 \qquad (20)$$

This is the assumed ambient seismic noise flux.

$$\frac{W_{amb}}{W_{max}(1\ \text{m})} = \frac{6.6 \times 10^{-8}}{1.1 \times 10^6} = 6 \times 10^{-14} \qquad (21)$$

The noise floor is therefore more than 130 dB below the signal that can be generated at a distance of 1 m from the source.

D. RANGE OF SIGNAL TRANSMISSION

The equation governing the rate of decay of the power flux in an absorbing medium is

$$\frac{dW}{W} = - \left(\alpha + \frac{2}{R}\right) dR \qquad (22)$$

where α is the absorption coefficient of the medium. With $\alpha = 0$, (22) merely states the inverse square law due to spreading. On integration, (22) gives

$$\ell n \frac{W}{W_o} = - 2 \ell n \frac{R}{R_o} - \alpha (R - R_o) \qquad (23)$$

where R_o and W_o refer to the initial values. W_o may be taken to be the maximum flux at $R_o = 1$ m. Converting (23) to logarithms to base 10,

$$10 \log \frac{W}{W_o} = - 20 \log \frac{R}{R_o} - \frac{10 \alpha}{2.303} (R - R_o) \qquad (24)$$

where all the terms in (24) are now in decibels.

Substituting

$$\frac{A}{\lambda} = \frac{10\alpha}{2.303}$$

where A is the attenuation in decibels per wave length

$$10 \log \frac{W}{W_o} = -20 \log \frac{R}{R_o} - \frac{A}{\lambda} (R - R_o)$$

and solving for λ:

$$\lambda = \frac{-A (R - R_o)}{10 \log \left[\frac{W}{W_o} \left(\frac{R}{R_o}\right)^2\right]}$$

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For R_o = 1 m and R >> 1 m

$$\lambda = \frac{-AR}{10 \log \left(R^2 \frac{W}{W_o}\right)} \tag{25}$$

and

$$f = \frac{v}{\lambda} = \frac{-10v \log \left(R^2 \frac{W}{W_o}\right)}{AR} \tag{26}$$

For rocks at depths of some hundreds of meters or more, A is generally ≤ 1/2. Occasionally, A may be as high as 1 (see Ref. D-10).

Substituting A = 1/2 and $W/W_o = 10^{-13}$ in equation (25), one finds that it should be possible to observe signals with a wavelength λ = 1.9 m at a distance R = 300 m, and signals with a wavelength of 7.1 m at a distance of 1 km.

Figure D-2 is a plot of the energy ratio, W/W_o, for various frequencies and distances, using V = 3 km/s and A = 1/2. Figure D-3 is the corresponding plot for A = 1. The frequencies that should be observable at 300 m are 1600 Hz and 800 Hz for A = 1/2 and A = 1 respectively. At 1 km they are 400 Hz and 200 Hz, respectively.

E. RESOLUTION

According to a criterion similar to Rayleigh's in optics, the attainable resolution is about half a wavelength. For a distance of 300 m between the boreholes, a wavelength of 2 m should generally be detectable, and a resolution of about 1 m is theoretically possible. With 1 km between holes, a wavelength of 8 m should generally be detectable, and the theoretical resolution is about 4 m. Somewhat lower resolutions would be expected in practice.

Since resolution is provided by the short-wavelength high-frequency components of the signal, it will probably be desirable to remove the lower frequencies from the recorded signals by digital filtering, prior to tomographic inversion.

The optimum pixel size for the computations is expected to be of the order of a wavelength. Take the example of 300 m between boreholes and a 2-m wavelength. The distance between boreholes is then 150 wavelengths. A grid of 100 × 100 or 150 × 150 might be appropriate, making the pixel dimension 3 × 3 m or 2 × 2 m. The grid and indeed the pixels need not be square; the vertical dimension of the grid can be adjusted to cover the depth range of interest.

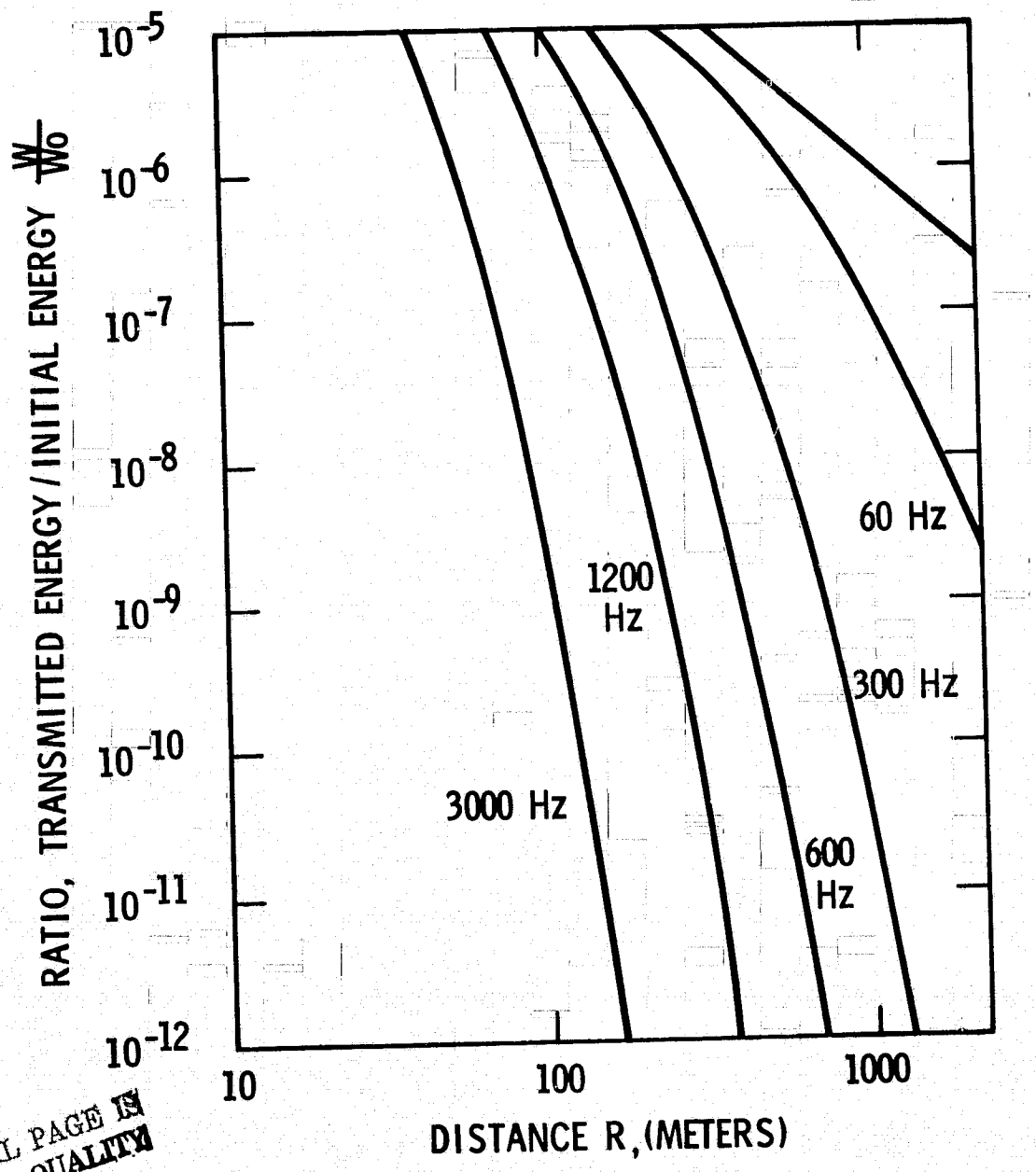

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Figure D-2. Seismic Energy Transmitted. Assumed attenuation 1/2 dB/wavelength. Velocity 3 km/s

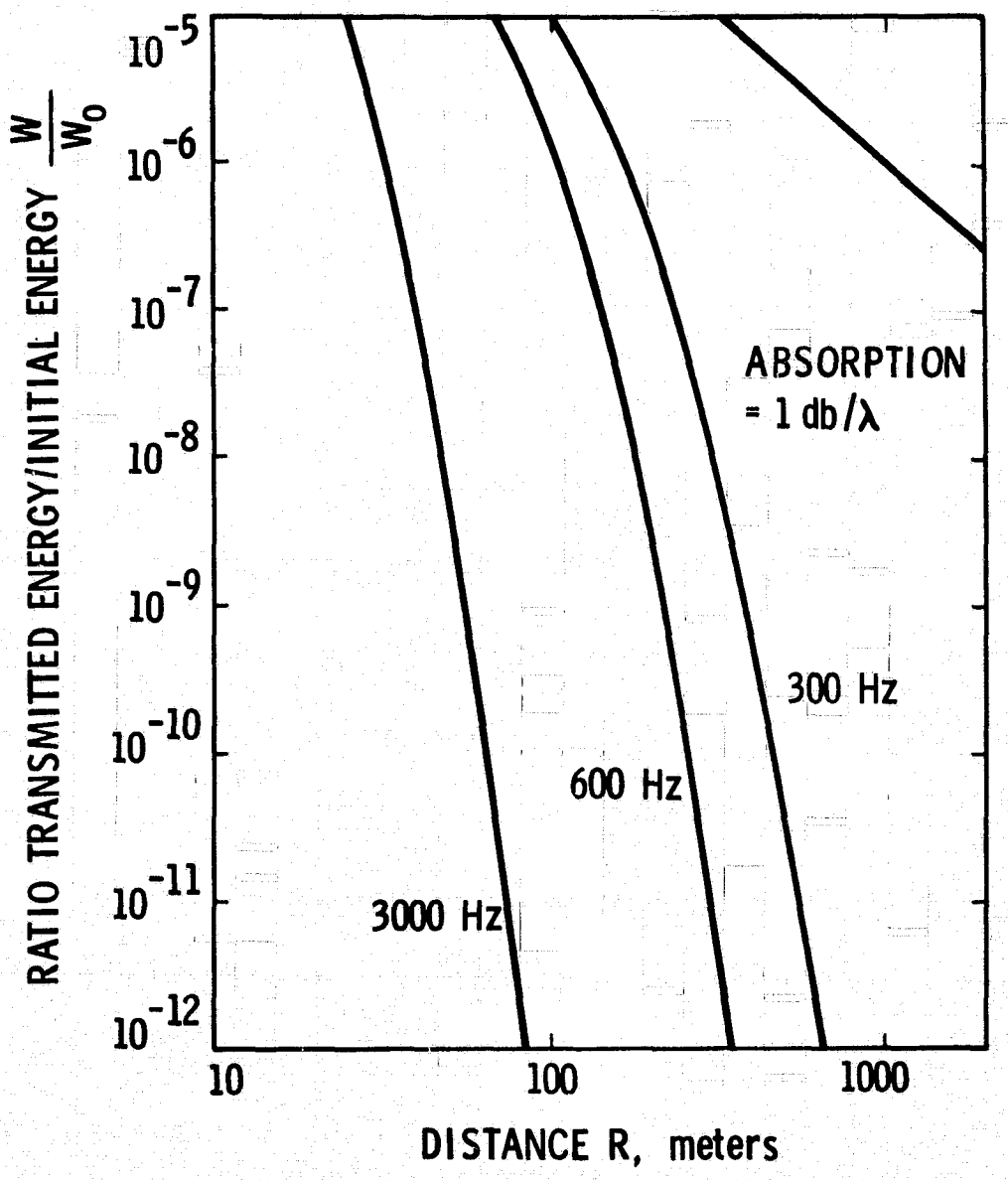

Figure D-3. Seismic Energy Transmitted. Assumed attenuation 1 dB/wavelength. Velocity 3 km/s

F. REFRACTION

Up to this point it has been assumed that the signal propagates along a straight line. Since velocity differences occur, refraction will take place.

This can be handled with an iterative procedure, as follows: Starting with assumed straight-line propagation, the tomographic inversion gives a first approximation to the velocity distribution. This approximate velocity distribution is used to calculate approximate ray paths, by these methods of refraction seismography. With these new ray paths, the tomographic inversion is repeated, and gives a second approximation to velocity distribution. The process is repeated until the solution converges.

G. ALTERNATIVE RAY PATHS

In general the signal recorded at a phone due to one shot will be a composite of the wave transmitted along the most direct path (the primary arrival) and waves arriving at the phone from a variety of other ray paths. Signals from different paths can generally be distinguished by utilizing the directivity of the phone pattern.

Consider a wave arriving at the phone location G_i at angle θ and at neighboring phones equally spaced on either side of G_i (Figure D-4). If the phones are closely spaced, the angles of arrival at neighboring phones will be approximately θ. Assuming that the phones are equally spaced at a distance d around G_i, the time delay of arrival at consecutive phones of the wave under consideration is

$$\Delta t = d \sin \theta / V_{eff}$$

where V_{eff} is the effective wave velocity. Thus, if the arrival time of the wave at a phone location G_i is t_o, then the phones at G_{-1}, G_{-2},. . . G_{-n} will receive the wave earlier at time $t_o - \Delta t$, $t_o - 2\Delta t$, . . . $t_o - n\Delta t$ and the phones at G_1, G_2, . . . G_n will receive the wave at $t_o + \Delta t$, $t_o + 2\Delta t$, . . . $t_o + n\Delta t$ respectively. Hence the wave at the phone location G_i can be identified by stacking the records of phones at G_{-1}, G_{-2}, . . . G_{-n} with a time delay of Δt, $2\Delta t$, . . . $n\Delta t$ with respect to record of phone G_i and also stacking the records of phones at G_1, G_2, . . . G_n with a time advance of Δt, $2\Delta t$, . . . $n\Delta t$ with respect to the record at G_i. Thus the arrival time t_o and the amplitude of the wave under consideration at G_i can be determined.

This method of processing will single out and enhance the wave arriving at a phone in a particular direction, and the waves arriving at the phone from other directions will cancel. Further the method of processing described above can be generalized to recover waves arriving at a phone from various directions and is applicable even when two waves arrive at a phone simultaneously.

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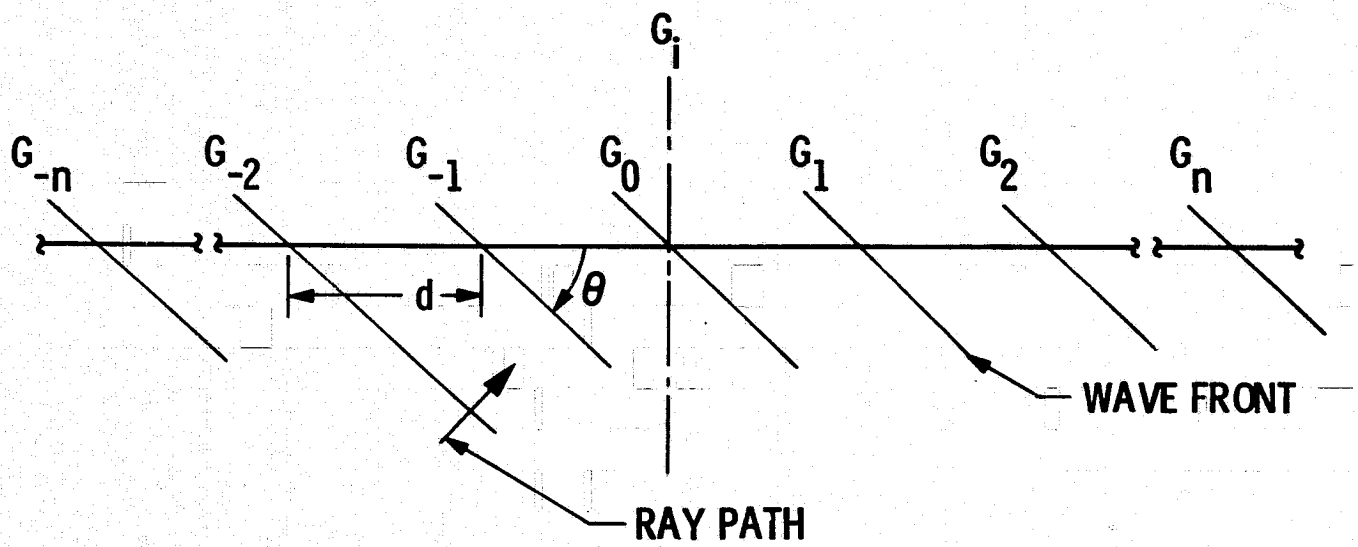

Figure D-4. Directional Processing of Signals to Identify Ray Path

The angular resolution of a set of transducers is given by

$$\theta = \lambda/S$$

where λ is the wavelength of the radiation and S is the distance between the first and last transducer. (This formula is familiar in optics and gives the resolving power of instruments, etc.) If, for example, the length S is 10 wavelengths, the angular resolution θ = 1/10 radian = 6°. The angular resolution does not depend on the total number of transducers occupying the length S provided there are enough of them. In directional processing it is assumed, however, that the arrival directions at the 2n + 1 individual receivers of the set are parallel (Figure D-4). This assumption implies the 2n + 1 phones are all receiving the same ray; tomography, on the other hand, assumes that the ray paths to different sensor locations are independent. If in order to provide good directionality the set length is 10 wavelengths and each set is treated as a single tomographic sensor location, the spacing of rays in the tomographic processing will be 10 times as great as if, for example, the tomographic processing is based on sensor locations only 1 wavelength apart. The spatial resolution will accordingly be 10 times coarser. There is thus a trade-off between spatial and angular resolution. To attain high spatial resolution, as is likely to be desired, directional processing will often have to be limited to moderate or low angular resolution.

Signals arriving along different ray paths should nevertheless usually be identifiable by directional processing. Multiple reflections, however, sometimes arrive at the phone along the same direction as the direct signal. With a transmission geometry, multiples generally will be weaker than direct arrival and will arrive later; thus the direct arrival should be distinguishable. Likewise, signals due to diffracted waves should be weaker than the direct arrival.

Some special cases of alternative paths are considered in the following sections.

H. LOW VELOCITY LAYERS

In refraction seismography from the surface, a low velocity layer bounded on both sides by higher velocity layers cannot be detected. The problem of a low velocity layer in hole-to-hole tomography is therefore considered. Two kinds of problems may occur: (1) Recognition of the presence and location of the low-velocity layer; (2) Preferential transmission of signal by the low-velocity layer (waveguide effect), so that the signal through a more direct high-velocity path is weaker and hard to recognize.

The problem in refraction seismography from the surface arises because a signal passing from a high-velocity to a low-velocity layer tends to be refracted across the low-velocity layer and does not travel

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along the layer (Ref. D-11). In hole-to-hole tomography, if the low-velocity layer is thick, source and phone locations can be within the layer and no difficulty arises in obtaining and recording transmission along the layer. If the layer is thin, or at high angle to the line from source to phone, it will not be practical to record the signal transmitted along the layer. Even though the signal is transmitted only across the layer, and this distance is small, the overall transmission time and signal strength will be affected. Unless the layer is much thinner than the wavelength or the pixel size, its presence should be indicated, after tomographic inversion, by a local change in the velocity or attenuation at the pixels where the seismic ray paths crossed the low-velocity layer.

Waveguide transmission can occur only in low-velocity layers thicker than one quarter the wavelength. For the velocity contrasts encountered in geology, the layer thickness must usually be greater than 4 times the wavelength. Thus thin layers will not act as waveguides.

Thick low velocity layers can guide high frequency waves in a manner similar to SOFAR, which is the phenomenon of long-distance sound propagation in a low-velocity channel in the ocean. It is instructive to look at typical SOFAR ray shapes and signal amplitudes to infer what such effects contribute to tomography. (A discussion of this phenomenon is given in Reference D-12).

In Figure D-5(a), the location of a low-velocity layer in the ocean is shown. The gradient of wave velocity is usually much steeper near the surface of the ocean and this leads to a simplified picture. In Figure D-5(b) the top layer is regarded as a perfect reflector and rays that penetrate to various depths are shown. Here both source and receiver are assumed to be within the low velocity layer. Path analysis shows that the first ray to arrive at the receiver is from the deepest path. The dark line shows the first arrival. The signals going along shallower paths arrive progressively later and the direct ray arrives last. Actual records from an explosive source in the ocean are shown in Figure D-6. Figure D-6(a) shows the main signal of about 1 sec duration followed by multiple reflection from the ocean bottom which is essentially a reverberation. In Figure D-6(b), the signal gradually rises and suddenly falls. The deepest rays arrive first, progressively larger signals due to shallower rays arrive later and the direct ray arrival has the largest amplitude. The fact that the direct ray carries the maximum signal is interesting for tomography because this is essentially straight-line propagation. Directional processing can attenuate wave arrivals from other, unwanted, directions but even so it is helpful that the direct arrival ray is strongest. The direct ray arrives last but because tomography need not utilize first arrivals, there would be no difficulty in processing.

If the source, receiver, or both are outside the low velocity layer, the direct arrival will again be strongest and may arrive earlier than any signal propagating along the low velocity layer. Directional processing may provide additional discrimination.

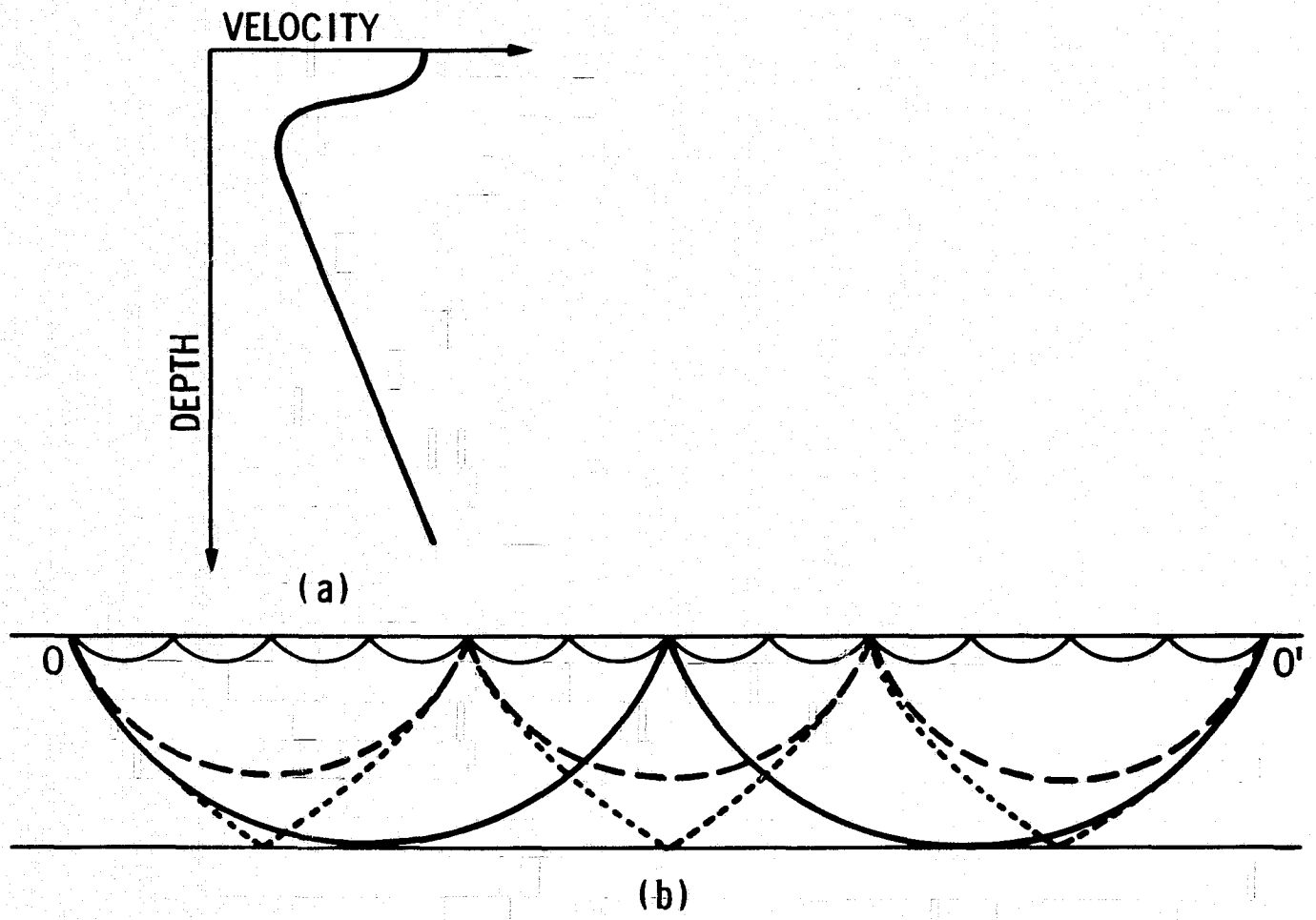

Figure D-5. Guided Waves in the Ocean (Schematic)
(a) Acoustic velocity vs depth
(b) Ray paths, assuming velocity minimum is at the surface
After Brekhovskikh (Ref. D-12)

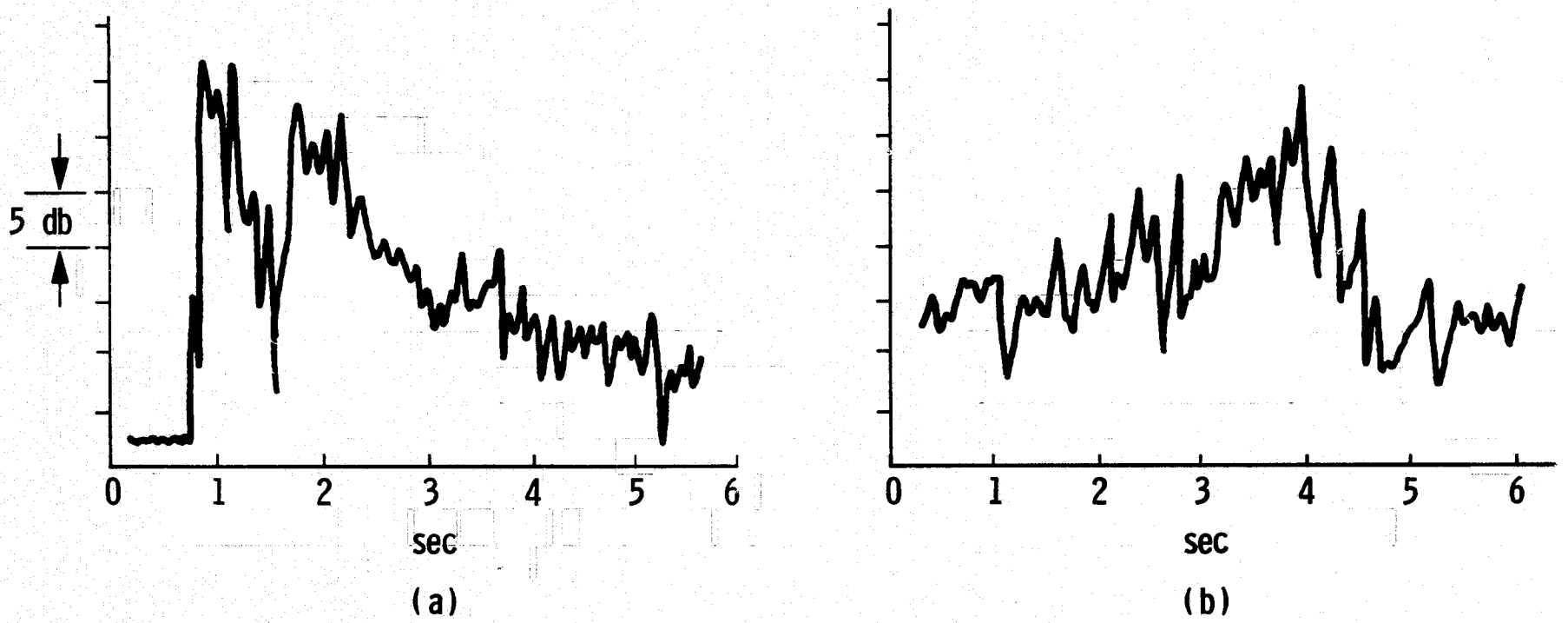

Figure D-6. Record of Sound from Underwater Explosion, Transmitted Through the Water
(a) At a small distance
(b) At a great distance (560 km)
After Brekhovskikh (Ref. D-12)

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I. TUBE WAVES

Tube waves are waves which travel along a cylindrical discontinuity. In hole-to-hole tomography, they are waves traveling along the boreholes.

There are two aspects of tube waves to be considered. A tube wave may be a source of unwanted interference as far as the signal sensed by a borehole is concerned. This may degrade the signal-to-noise ratio in the tomographic reconstruction. The other aspect is that a strong tube wave in the source borehole may produce body waves of enough strength to be useful for tomography. This introduces the possibility that a single tube wave could replace many downhole sources.

Consider first tube waves as unwanted interference. Body waves produced by a source away from a borehole reach various cross-sections of the borehole at different times and distort the borehole cross-section. This local pinching sends out borehole waves in both directions. The wave motion in the borehole is a superposition of the waves produced by the distortions at various positions and times. (Reference D-13 has a good discussion of tube waves.) Figure D-7 shows signals from a nearby source recorded at various points along a borehole. The first arrival is the body wave; the second arrival is the tube wave. The tube wave is lower in frequency (broader, in the time record) and can easily be distinguished from the direct body wave. In addition, directional processing will eliminate the tube waves, which propagate along the borehole axis.

The possibility of using a strong borehole wave as a source for tomography will be considered next. Assume that a shot at the surface or a source of high pressure with a burst diaphragm drives a shockwave in the borehole fluid. Each element of the borehole fluid is subjected to a step change of pressure as the wave moves down. The wave motion into the rock may then be regarded as due to a number of spherical cavities with step change of pressure in each. Each such source produces a particle displacment spike as given by equation (15). A phone in another borehole sees a superposition of such spikes arriving at different times and from different directions. The received signal is therefore broadened considerably. Directional processing will enhance the signal from a wanted direction and minimize the signals from other directions. The problem is to find how effective such a procedure is in recovering the spiky shot signal from such broad measured signals. To resolve the signal well, high angular resolution will be needed in the directional processing. As pointed out above, this is inconsistent with using closely spaced rays for the tomographic reconstruction, as needed for high spatial resolution. Thus, use of a borehole shockwave as the signal source will not permit as good spatial resolution as a sequence of signal shots at various points in the borehole.

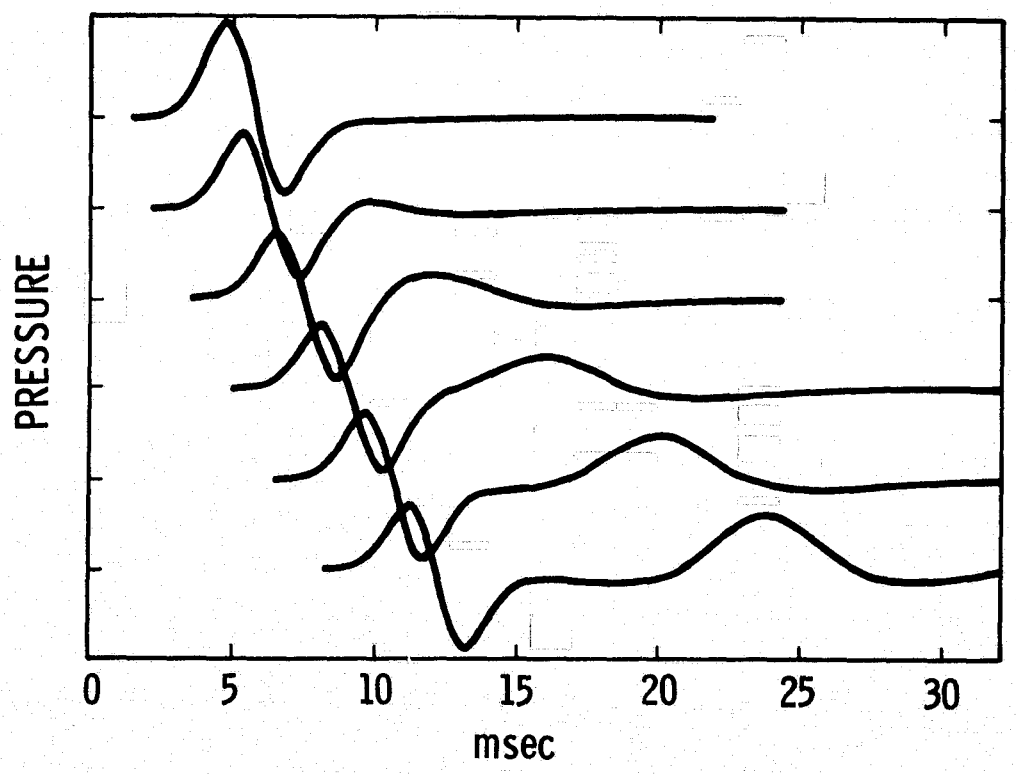

Figure D-7. Pressure Signals in a Borehole Due to a Pressure Pulse in a Small Cavity Near the Hole
Form of pulse: $p(t) = p_o$ erf (t)
Records at 3.3 m intervals along hole
Signals normalized by multiplying by source-phone distance to remove inverse square law decay of body wave.
After White (Ref. D-13)

J. PHONES AND RECORDING SYSTEM

In principle, either downhole hydrophones or downhole geophones could be used. Experience with downhole hydrophones, it appears, indicates that they tend to be noisy and very susceptible to acoustic impulses travelling along the cable to which they are attached. Geophones, clamped to the wall of the borehole, are probably preferable. The cable to which the geophones are attached should, if practicable, be slackened to reduce seismic transmission along it.

Either single-axis or 3-axis geophones could be used. Single-axis phones are cheaper. A disadvantage is that a compressive pulse transmitted horizontally from a source in one borehole to a phone in another will have no vertical component and therefore will not register on a vertical-axis geophone. A partial solution is to keep the source and geophones at different depths (Ref. D-14).

Three-axis geophones do not suffer from the difficulty just mentioned. Also, with their use it is much simpler to distinguish shear wave arrivals. This helps in picking events on the record. In addition, if separate compression and shear arrivals can be identified, tomographic processing can be carried out for each, separately, thus providing additional information about the reservoir characteristics.

To obtain high spatial resolution in the tomography, each geophone, or a group extending only over a short depth interval (a wavelength or so), should be individually recorded. Thus, a multiconductor downhole cable will be needed (or a wideband downhole telemetry system).

The amplifier and recorder used, as well as the analog-to-digital converter, must be capable of handling higher frequencies than are employed in conventional seismic work.

If multiple nearby boreholes are available, together with enough downhole phones, it may be desirable to place phones in several holes and record simultaneously the signals received in all these holes from shots in a single borehole. Tomographic reconstruction would then be carried out separately for each combination of source borehole and phone borehole.

If only one borehole is available, tomography is still possible between shot points in the borehole and a geophone array on the surface, or vice versa. The region where ray paths intersect at appreciable angles will, with this geometry, usually be close to the hole and shallower than the shot points, so it may be hard to get adequate coverage of the reservoir. Also, the seismic paths will be fairly long (hole-to-surface) and a weathered layer may be encountered; losses may therefore be high, limiting the frequency that can be utilized and hence the resolution. There may still be significant advantage when compared to reflection seismography from the surface: paths lengths, including the path length through the weathered layer, are only 1-way rather than 2-way, and the usual low reflection coefficients introduce much smaller losses in transmission than in reflection.

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K. WALL REFLECTIONS

The effects of reflections at the borehole wall on the signal strength need to be investigated. It is assumed that the pressure at the wall is limited to the elastic range, as discussed above. A cased hole will be considered first. It will be shown that because the casing thickness and the bore diameter are small compared to the wavelengths used for seismic tomography, reflection losses at the wall are small.

Let us examine first a seismic wave impinging at normal incidence upon the interface between 2 semi-infinite media. This is equivalent to a wave of infinite frequency impinging at normal incidence upon the interface between 2 media of finite thickness. The reflection coefficient is

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

and the transmission coefficient

$$T = \frac{2Z}{Z_2 + Z_1}$$

Here

$Z_1 = \rho_1 v_1$ and $Z_2 = \rho_2 v_2$,

Z_1 (water) $= 1.5 \times 10^6$ kg/m^{2}s

Z_2 (steel) $= 45 \times 10^6$ kg/m^{2}s

Therefore, for waves incident from water to steel,

$$R = 0.935$$

$$T = 1.935$$

The transmitted intensity is

$$\frac{p_{in}^2 \, T^2}{Z_2} = \frac{p_{in}^2 \, (1.935)^2}{45 \times 10^6 \text{ kg/m}^2\text{s}}$$

and is much smaller than the incident intensity

$$\frac{p_{in}^2}{1.5 \times 10^6 \text{ kg/m}^2 \text{ s}}$$

The ratio of intensities is

$$\frac{I_t}{I_i} = \left(\frac{2Z_2}{Z_2+Z_1}\right)^2 \frac{1}{Z_2} \Bigg/ \frac{1}{Z_1} = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}$$

$$= 4\,\frac{1.5 \times 45}{(46.5)^2} = 0.125$$

The transmitted intensity for waves of infinite frequency is therefore 1/8 the incident intensity for incidence from water to steel or from steel to water.

Consider next a wave of wavelength λ impinging at normal incidence on a layer of steel of thickness d, surrounded by water. It can be shown that

$$T = \sqrt{\frac{1}{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi d}{\lambda}\right)}}$$

and

$$R = \sqrt{\frac{\frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi d}{\lambda}\right)}{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi d}{\lambda}\right)}}$$

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where

$$m = \frac{Z_1}{Z_2}$$

$T^2 + R^2 = 1$ as is required for energy conservation.

T is an oscillatory function because of the term

$$\sin^2\left(\frac{2\pi d}{\lambda}\right) = \sin^2\left(\frac{2\pi df}{v_1}\right)$$

where

f = frequency. Figure D-8 shows T vs d·f.

For the borehole problem, we are interested in frequencies of about 1 kHz and the casing thickness is 5-10 mm.

Therefore, $d \cdot f \simeq (10^{-3}\ \text{MHz})\ (10\ \text{mm}) = 10^{-2}\ (\text{mm MHz})$

From Figure D-8, it is evident that T is ≃ 1. More exactly, for d = 1 cm, the quantity

$$\sin^2\left(\frac{2\pi df}{v_1}\right) = \sin^2\left[\frac{2\pi(1)\ (1000)}{150000}\right] = 0.00175$$

$$\left(m - \frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi d}{\lambda}\right) = \left(\frac{45}{1.5} - \frac{1.5}{45}\right)^2\ (0.00175) = 1.57$$

$$T = \frac{1}{\sqrt{1 + \frac{1.57}{4}}} = 0.85$$

and

$$R = \sqrt{1 + T^2} = 0.53$$

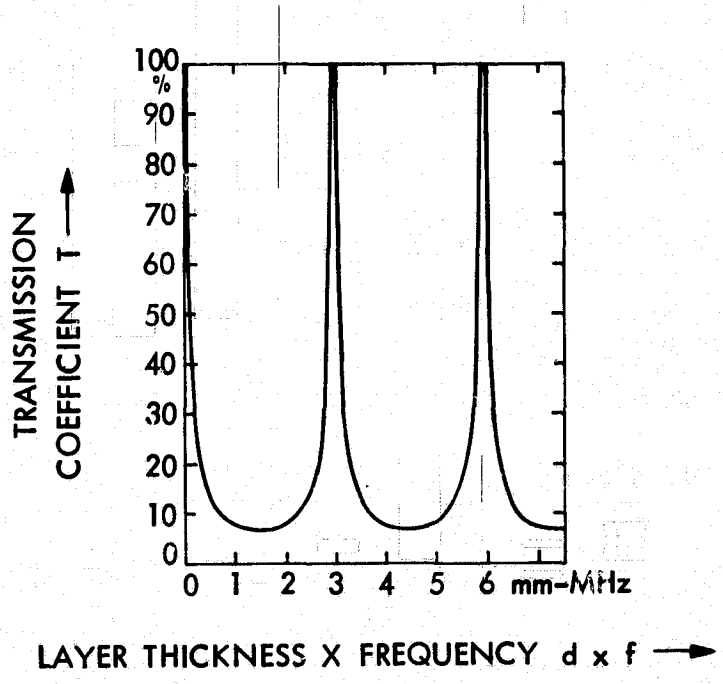

Figure D-8. Transmission Coefficient for Seismic Wave Impinging on Layer of Steel Immersed in Water

Normal Incidence
d = layer thickness
f = frequency
After Krautkramer and Krautkramer (Ref. D-15)

For d = 0.5 cm

$$T = \frac{1}{\sqrt{1 + 0.0985}} = 0.954$$

At lower frequencies T = 1. The casing is thus virtually transparent for the frequencies of interest.

At other angles of incidence, the formulas are more complicated and are discussed in Reference D-12. For thin plates, as the thickness goes to zero, reflection tends to zero even at the angle of total internal reflection, as the following discussion shows. Total reflection occurs when

$$d = \left(n + \frac{1}{2}\right) \frac{\lambda_t}{\cos \gamma_2}$$

Here n is an integer,

λ_t = wavelength of transmitted shear waves

and γ_2 is the angle of refraction for transmitted shear waves.

For

$$d < \frac{1}{2} \frac{\lambda_t}{\cos \quad _2}$$

there is no internal reflection. Referring to Figure D-9, Snell's law is

$$\frac{\sin \theta_1}{v_1} = \frac{\sin \theta_2}{v_2} = \frac{\sin \gamma_2}{b_2}$$

v = compressional wave speed

b = shear wave speed.

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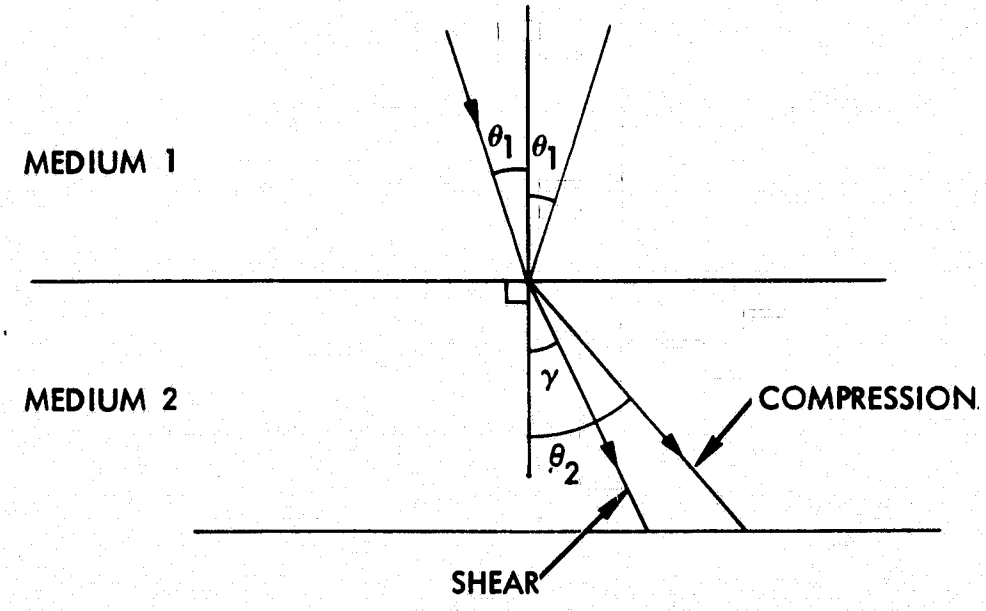

Figure D-9. Geometry of Transmission and Reflection of a Compression Wave Impinging on an Interface

At $\theta_2 = 90°$ (total reflection)

$$\frac{\sin \theta_2}{v_1} = \frac{1}{v_2} = \frac{\sin \gamma_2}{b_2}$$

i.e.

$$\gamma_2 = \text{arc sin} \frac{b_2}{v_2}$$

$$\cos \gamma_2 = \frac{\sqrt{v_2^2 - b_2^2}}{v_2}$$

Thus the condition for no total reflection is

$$d < \frac{1}{2} \frac{\lambda_t \, v_2}{\sqrt{v_2^2 - b_2^2}} = \frac{1}{2} \frac{b_2}{f} \frac{v_2}{\sqrt{v_2^2 - b_2^2}}$$

or

$$f < \frac{1}{2} \frac{b_2}{d} \frac{v_2}{\sqrt{v_2^2 - b_2^2}}$$

For steel

$v_2 = 5.9 \times 10^3$ km/s

$b_2 = 3.23$ km/s

and taking d = 5mm = 5×10^{-6} km

$$f < \frac{1}{2(5 \times 10^{-6})} \frac{3.23 \times 5.9}{\sqrt{(5.9)^2 - (3.23)^2}}$$

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i.e.

$$f < 3.86 \times 10^5 \text{ Hz} = 386 \text{ kHz}$$

Accordingly, no total internal reflection will occur even at the angle of total internal reflection.

Similar calculations can be made for the steel/cement interface, or for the water/rock interface of an uncased hole, and similar results will be obtained. Further, the wavelength of longitudinal waves at 1000 Hz in water is 150000/1000 = 150 cm and is therefore much larger than the size of the borehole (radius ~ 10 cm). The pressure near the borehole is not due to propagating sound waves but is essentially quasisteady. The problem is one of static elasticity with different materials in contact. In such problems there are no reflections etc. associated with dynamic phenomena. True wave motion occurs only at distances greater than a few wavelengths away from the source. A correct solution to this problem would therefore show smaller reflections than indicated by the plane wave analysis above.

C-4

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APPENDIX E

ANALYSIS OF HEAT LOSSES AND CASING TEMPERATURES IN STEAM INJECTION WELLS WITH ANNULAR COOLANT WATER FLOW

Lloyd H. Back and Robert F. Cuffel

APPENDIX E

ANALYSIS OF HEAT LOSSES AND CASING TEMPERATURES IN STEAM INJECTION WELLS WITH ANNULAR COOLANT WATER FLOW

A. ANALYSIS OF COOLANT WATER FLOW IN ANNULUS

Wellbore heat transfer analyses have been carried out by Moss and White (Ref. E-1) and by Ramey (Ref. E-2), and subsequently by others (Refs. E-3 and E-4), but there apparently has not been an investigation of circulating water through the annulus to cool the casing and to pick up some of the heat that would otherwise be lost of the surrounding rock.

The wellbore configuration considered here is depicted in Figure E-1. Steam flows through the insulated tubing and water flows through the annulus between the sealed insulation and the casing from the ground level. Heat is transferred from the steam flow through the tubing and insulation to the water flow. Part of this heat is picked up by the water flow, and part is transferred through the casing and cement to the surrounding rock. At the bottom of the wellbore the steam and water flows mix before entrance into the formation.

In the analysis that was carried out, quasi-steady heat transfer was considered, i.e., the thermal capacity of the tube wall and casing and to a lesser extent the insulation and cement were not taken into account, but the heat transfer from the cement to the surrounding rock was taken as time dependent in the way considered by Ramey (see Ref. E-2) for the infinite radial rock. Consequently, the analysis does not account for the initial time period of injection when the wellbore is being heated. More elaborate analysis is required to account for this initial transient.

An energy balance on an elemental length dL of the annulus through which water flows is given by

$$dQ_s = \dot{m}_w C_{p_w} dT_w + dQ_r \tag{1}$$

where the differential heat transfer rate dQ_s from the condensing steam flow is

$$dQ_s = -\dot{m}_s dh_s = 2\pi r_i U_i (T_s - T_w) dL \tag{2}$$

and the differential heat transfer rate dQ_r to the surrounding rock is

$$dQ_r = 2\pi r_2 U_2 (T_w - T_h) dL \tag{3}$$

Changes in kinetic and potential energy of the steam flow and potential energy of the water flow were neglected since they are relatively small compared to enthalpy changes.

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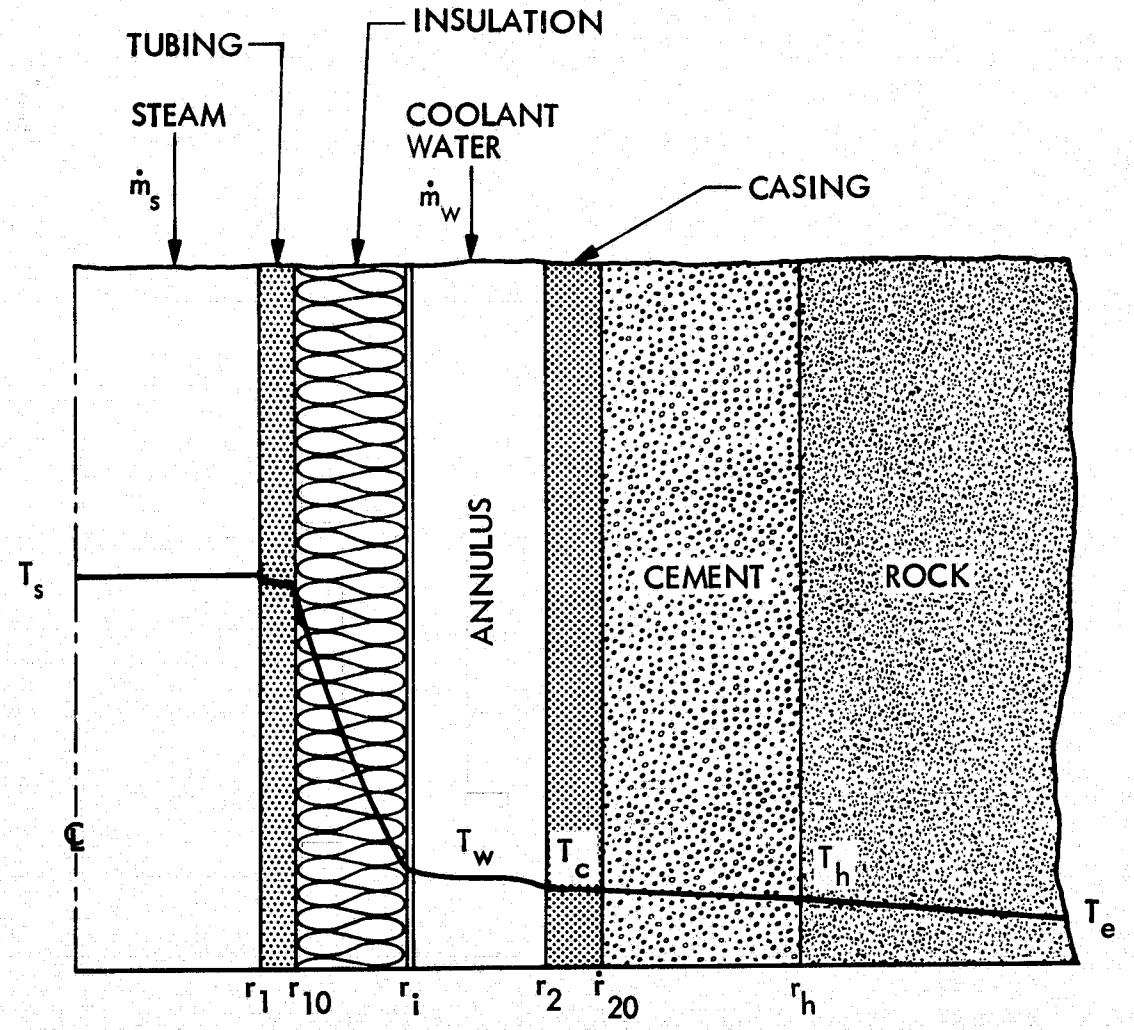

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Figure E-1. Schematic of Wellbore and Temperature Distribution

The overall heat transfer coefficients on the inside U_i and the outside U_2 of the annulus are given by

$$U_i = \frac{1}{\frac{r_i}{r_1}\frac{1}{h_{c_s}} + \frac{r_i}{k_t}\ln\frac{r_{10}}{r_1} + \frac{r_i}{k_i}\ln\frac{r_1}{r_{10}} + \frac{1}{h_{c_i}}}; \tag{4}$$

$$U_2 = \frac{1}{\frac{1}{h_{c_o}} + \frac{r_2}{k_2}\ln\frac{r_{20}}{r_2} + \frac{r_2}{k_c}\ln\frac{r_h}{r_{20}}} \tag{5}$$

Each term in the denominator in equations 4 and 5 is a resistance to heat transfer. Since heat transfer coefficients h_{c_s} for condensing steam are relatively large, e.g., McAdams, (Ref E-5) and resistances of the metal tube and casing are orders of magnitude smaller than the insulation and cement, the overall heat transfer coefficients are approximately

$$U_i \simeq \frac{1}{\frac{r_i}{k_i}\ln\frac{r_i}{r_{10}} + \frac{1}{h_{c_i}}}; \quad U_2 \simeq \frac{1}{\frac{1}{h_{c_o}} + \frac{r_2}{k_c}\ln\frac{r_h}{r_{20}}} \tag{4a)(5a}$$

The film side heat transfer coefficients h_{ci} and h_{co} for the water flow were evaluated for fully developed laminar flow, $h_c d_h/k_w \simeq 3.65$, since the water flow Reynolds numbers $Re = ud_h/\nu_w$ where d_h is the hydraulic diameter $d_h = d_2 - d_i$, were below 2000 for the relatively small water flow rates of interest, and the ratio of L/d_h was so large that entrance region effects would be negligible. For example, for the dimensions of the wellbore subsequently described, the Reynolds number for a water flow rate $\dot{m}_w$ of 100 and 1000 lb/hr is 135 and 1350, respectively, evaluating water properties at about 150°F. In the calculations, the inside and outside heat transfer coefficients h_{ci} and h_{co} were taken to be approximately the same and equal to h_c. Natural convection effects in the annulus which may become important at the lowest water flow rates were not taken into account in the analysis. There is little information on combined forced and natural convection effects in annuli with the large ratios of L/d_h typical of steam injection wells.

Relating the differential heat transfer rate dQ_r from the outside of the annulus to that to the surrounding rock by the Ramey formulation

$$dQ_r = 2\pi r_2 U_2 (T_w - T_h)dL = \frac{2\pi k_e (T_h - T_e)dL}{f(T)} \tag{6}$$

gives the temperature difference between the water and the outside of the cement T_h as

$$T_w - T_h = \frac{\xi}{f + \xi} (T_w - T_e) \tag{7}$$

where

$$\xi = \frac{k_e}{r_2 U_2} \tag{8}$$

The function f depends upon the dimensionless time $T = \alpha_e t / r_h^2$ as given by Ramey.

By combining equations 1, 2, 3 and 7, a differential equation for the variation of water temperature with depth was obtained as follows

$$\frac{dT_w}{dL} + \beta T_w = \gamma \tag{9}$$

where

$$\beta = \frac{2\Pi}{\dot{m}_w C_{P_w}} \left[r_i U_i + r_2 U_2 \frac{\xi}{f + \xi} \right] \tag{10}$$

$$\gamma = \frac{2\Pi}{\dot{m}_w C_{P_w}} \left[r_i U_i T_s + r_2 U_2 \frac{\xi}{f + \xi} T_e \right] \tag{11}$$

The solution of the Bernoulli equation 9 is given by

$$T_w = e^{-\beta L} \left[\int_o^L \gamma \, e^{\beta L} \, dL + T_{w_i} \right] \tag{12}$$

For the subsequent calculations, the frictional pressure drop of the condensing steam and the increase in pressure due to gravity were neglected to first order so that the entering steam temperature T_s was taken to be constant along the wellbore. Calculations of pressure variation with depth for steam flow in Appendix F indicate that the variation in saturation temperature would be relatively small. The variation of surrounding rock temperature T_e with depth was taken to be linear, i.e.,

$$T_e = T_g + cL \tag{13}$$

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where c is the geothermal gradient and T_s is the surface geothermal temperature. Other variations of T_e as well as T_s could be treated, too. With the prior assumptions the integral in equation 12 was evaluated analytically.

The total heat transfer rate Q_r to the surrounding rock is then obtained by integration of equation 3

$$Q_r = \int dQ_r = 2\pi r_2 U_2 \int_o^L (T_w - T_h)dL = 2\pi r_2 U_2 \frac{\xi}{f + \xi} \int_o^L (T_w - T_e)dL \quad (14)$$

where the last equality follows by using equation 7. Substitution of T_w and T_e from equations 12 and 13 into equation 14 and subsequent integration allows the evaluation of Q_r.

The total heat transfer rate Q_s from the steam flow is obtained by integration of equation 1

$$Q_s = \int dQ_s = \dot{m}_w C_{p_w} (T_w - T_{w_i}) + Q_r \quad (15)$$

The steam enthalpy h_s at depth L is given by integration of the first identity in equation 2

$$h_s = h_{s_i} - \frac{Q_s}{\dot{m}_s} \quad (16)$$

Note that the water temperature T_w and total heat transfer rate Q_r to the formation are independent of the steam flow rate $\dot{m}_s$, but the steam enthalpy h_s at depth L obviously depends upon $\dot{m}_s$ through equation 16.

The casing temperature T_c is determined from the continuity of the differential heat transfer rate dQ_r across the cement and into the surrounding rock

$$dQ_r = \frac{2\pi(T_c - T_h)dL}{\frac{1}{k_c} \ln \frac{r_h}{r_{20}}} = \frac{2\pi k_e (T_h - T_e)dL}{f(\xi)} \quad (17)$$

which upon solving for T_c gives

$$T_c = T_h + \frac{k_e}{k_c} \ln \frac{r_h}{r_{20}} \frac{1}{f} (T_h - T_e) \quad (18)$$

Relating T_h to T_w by equation 7 then gives the casing temperature T_c.

For adiabatic mixing of the steam and water flows at the bottom of the wellbore before entrance into the formation, the mixture enthalphy h_m is given by

$$h_m = \frac{\dot{m}_s}{\dot{m}_s + \dot{m}_w} h_s + \frac{\dot{m}_w}{\dot{m}_s + \dot{m}_w} h_w \qquad (19)$$

The mixture quality χ_m (vapor mass fraction) can then be obtained in the usual way from

$$\chi_m = \frac{h_m - h_{w_m}}{h_{fg}} \qquad (20)$$

where h_{w_m} and, the latent heat of vaporization, h_{fg} are evaluated at the saturation pressure of the mixture.

B. CALCULATIONS

The preceding analysis was programmed for numerical evaluation on the UNIVAC 1108 computer. The example considered was for an injection well with a depth L of 2500 ft. The borehole size d_h was taken to be 9.625 in. with a 7 in., 26 lb, J-55 casing (d_{20} = 7.00 in.; d_2 = 6.276 in.) and 2-7/8 in., 6.4 lb, J-55 steam tubing (d_{10} = 2.875 in.; d_1 = 2.441 in.). The tubing insulation thickness $r_1 - r_{10}$ was taken to be 0.75 in. so that the annulus gap $r_2 - r_i$ was a little less than an inch, being 0.95 in. The thermal conductivity k_i of the insulation was varied from 0.02 to 0.10 BTU/(hr-Ft-°F); the higher value being typical of grannular material and the lower value typical of fiberous and foam materials, to study the influence of variation in the thermal conductivity. The thermal conductivity of the cement k_c, presumed to be wet, was taken to be 0.5 BTU/(hr-Ft-°F). The surrounding rock thermal conductivity k_e was taken to be 1.4 BTU/(hr-Ft-°F) and thermal diffusivity α_e = 0.04 Ft^2/hr. The surface temperature T_g was presumed to be 70°F and the geothermal gradient, c = 0.0083°F/Ft.

Steam was presumed to be injected at a saturation pressure of 1500 psia for which the saturation temperature T_s = 596°F. The availability of water and steam was presumed to be 500 BWPD (i.e., $\dot{m}_s + \dot{m}_w$ = 7250 lb/hr) and the entering water temperature T_{w_i} was taken to be 70°F. The energy rate Q_i to produce the steam from water, $\dot{m}_s(h_{s_i} - h_{w_i})$, was taken to be constant at a value of 7×10^6 BTU/hr corresponding to that required to generate 70% quality steam with no coolant water flow. A range of water flow rates $\dot{m}_w$ from 50 to 1000 lb/hr was investigated after injection of steam and water for one week [f(T) = 2.27]. Since the calculations were based on the availability of water and steam being fixed, i.e., $\dot{m}_s + \dot{m}_w = 7250 \frac{lb}{hr}$, then as the water flow rate was increased, the steam flow rate was decreased.

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The water should be injected at a pressure p_{w_i} such that the static pressure p_w at the bottom of the well is about the same as the steam pressure there, i.e.,

$$p_w \approx p_s = p_{w_i} + W_w L - \Delta p_f \tag{21}$$

An estimate of the injection water pressure, neglecting the frictional pressure drop Δp_f and steam pressure change gives a value of p_{w_i} of about 420 psia, so that water injection pressure should be on the order of 500 psia. The corresponding saturation temperature of water at 500 psia is 467°F so that boiling would not occur at lower temperatures.

C. RESULTS

Results of the calculations are shown in Figures E-2 to E-5. In Figure E-2, the variation of water temperature with depth is shown for two values of the thermal conductivity k_i of the insulation of 0.10 and 0.02 BTU/(hr-Ft-°F) and at water flow rates $\dot{m}_w$ of 50 and 1000 lb/hr. At the lower water flow rate the water temperature rise was more abrupt because of the slower moving water, but at larger depths there was little difference in water temperatures with flow rate because of the asymptotic nature of the variation of water temperature with depth. This trend can be explicitly seen by evaluation of the integral in equation 12 by using an average value for the rock temperature $\overline{T}_e$ to obtain

$$T_w = \frac{\gamma}{\beta}\left(1 - e^{-\beta L}\right) + T_{w_i}\, e^{-\beta L} \tag{22}$$

where

$$\frac{\gamma}{\beta} = \frac{r_i U_i T_s + r_2 U_2 \dfrac{\xi}{f+\xi}\,\overline{T}_e}{r_i U_i + r_2 U_2 \dfrac{\xi}{f+\xi}} \tag{23}$$

Thus, in the limit of large depths $L \to \infty$ where $e^{-\beta L} \to o$, the water temperature $T_w \to \frac{\gamma}{\beta}$, becomes independent of the water flow rate $\dot{m}_w$ and initial water temperature T_{w_i}, and increases slightly with the increasing rock temperature T_e. There was a large influence of the thermal conductivity k_i of the insulation, with lower values considerably reducing the water temperature rise because of the larger thermal resistance to heat transfer from the steam flow.

The casing temperature T_c increases with depth like the water temperature as indicated in Figure E-3 where similar trends are observable, except that the casing temperature was less than the water temperature because of heat transfer into the surrounding rock. Higher water flow rates reduced the casing temperature more than lower water flow rates.

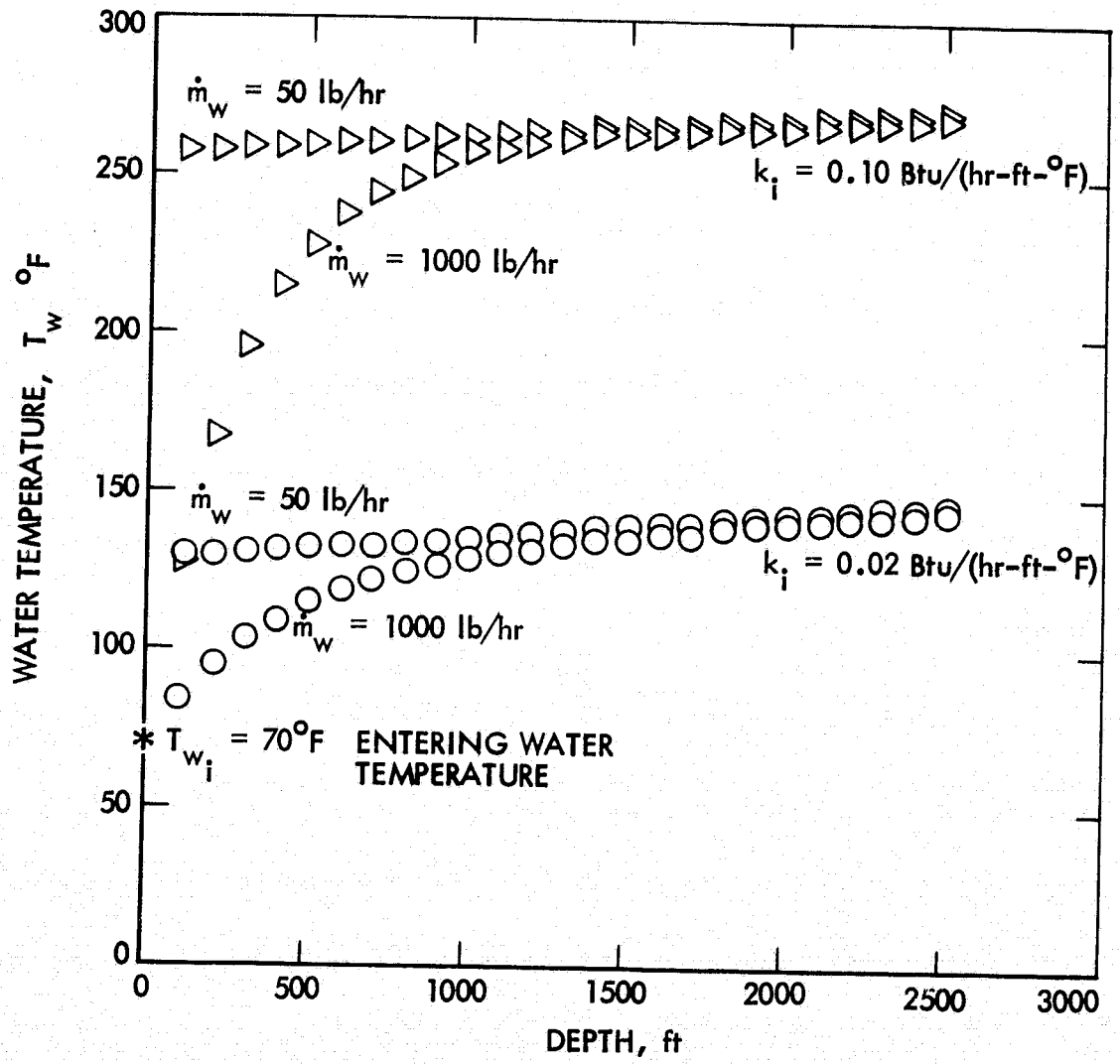

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Figure E-2. Coolant Water Temperature Variation With Depth
t = 1 Week

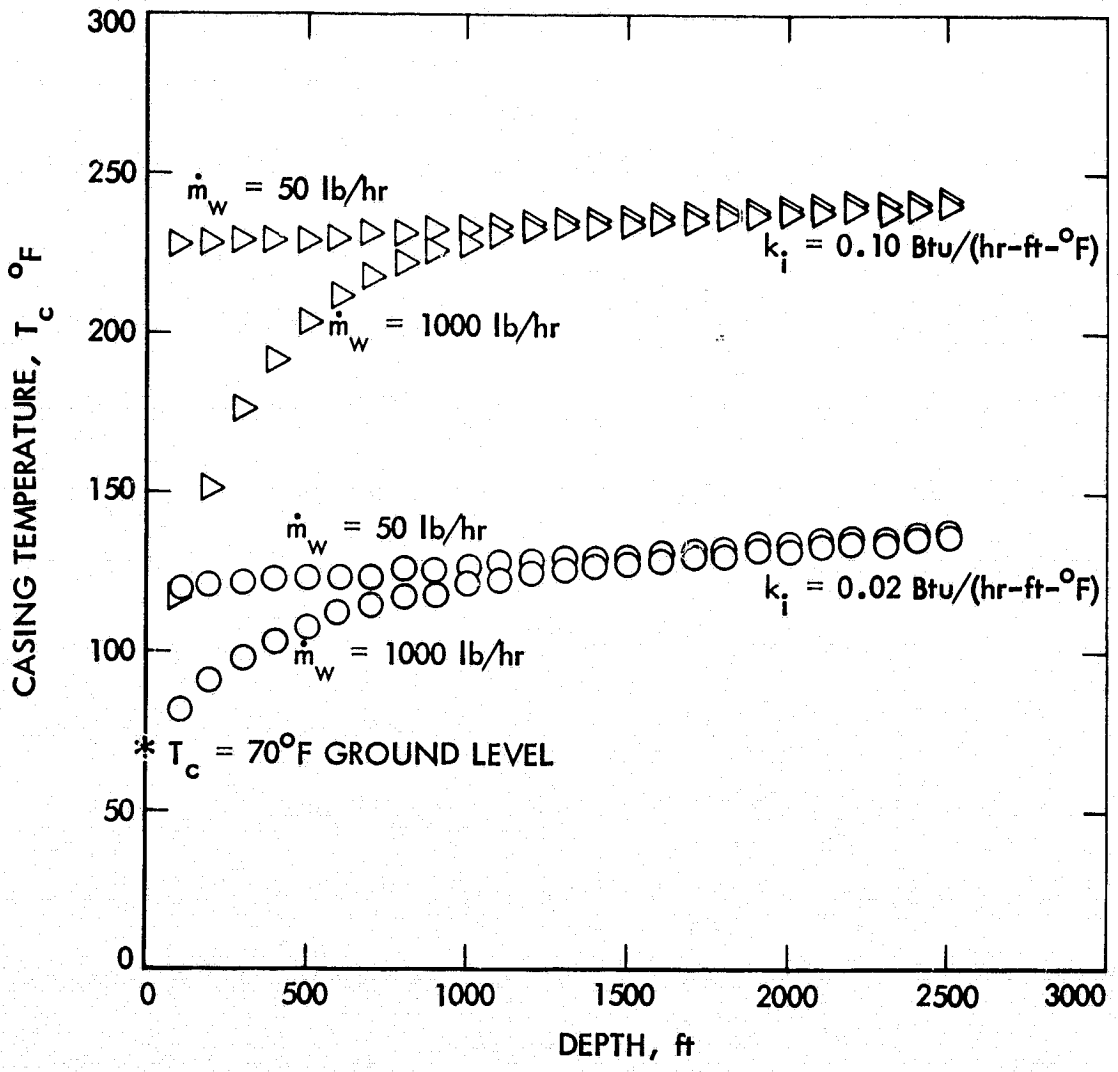

Figure E-3. Casing Temperature Variation With Depth
t = 1 Week

Changes in well bottom casing temperature T_c due to steam injection can be obtained from Figure E-3 by subtracting the rock temperature T_e which amounts to 91°F at 2500 ft for the example considered. Thus, the changes in well bottom casing temperature amounted to about 45°F and 150°F for values of k_i = 0.02 and 0.10 BTU/(hr-Ft-°F), respectively, the former change being rather small.

The percent energy loss rate to the surrounding rock is shown in Figure E-4 for the entire well depth of 2500 ft and at 1000 ft as a function of water flow rate $\dot{m}_w$ and insulation thermal conductivity k_i. This quantity is defined as the ratio (times 100%) of the energy rate lost by heat transfer to the surrounding rock $\dot{Q}_r$ divided by the energy rate required to produce the steam from water $\dot{m}_s(h_{s_i} - h_{w_i})$. In general, the % energy loss rate decreased with the lower thermal conductivity insulation, as would be expected, and with coolant water flow rate. For the lower values of insulation thermal conductivity, there was a greater percentage reduction in energy loss with increasing coolant water flow rate than for the higher thermal conductivities (see Table 1). The amount of heat picked up by the water flow $\dot{Q}_w = \dot{m}_w C_{p_w} (T_{w_L} - T_{w_i})$ ranged up to about 20% of the heat lost from the steam flow at the highest water flow rate considered as indicated by the values of $\dot{Q}_w/\dot{Q}_s$ given in Table 1. At a depth of 1000 ft with the higher thermal conductivity k_i of 0.10 BTU/(hr-Ft-°F), the percent energy loss rate was about 6% at low water flow rates and 4.5% at a water flow rate of 1000 lb/hr (see Figure E-4). For the lower thermal conductivity insulation k_i = 0.02 BTU/(hr-Ft-°F), the percent energy loss rate at a depth of 1000 ft was less than 2%, and for the entire well depth of 2500 ft was about 4%.

A final view of the results is shown in Figure E-5 where the steam quality χ_m after mixing of the steam and water flow at the bottom of the wellbore is indicated. The mixture quality was relatively constant with coolant water flow rate since the entering steam quality χ_i at ground level increased for the constant energy rate $\dot{Q}_i$ input. Consequently, even though more water coolant mixes with the steam, the higher initial quality of the steam leads to small changes in entering mixture quality at the formation. In fact, there was a slight increase in mixture quality with coolant water flow rate. For the insulation with lower thermal conductivity, the mixture quality was reduced less because of lower heat transfer and thus condensation in the steam flow. To avoid using too high quality entering steam and heater scaling problems, lower coolant water flow rates should be employed. Alternatively, if less energy is used to produce the smaller amount of steam $\dot{m}_s = 7250 - \dot{m}_w$, then the mixture quality at the formation would be lower than those values shown in Figure E-5.

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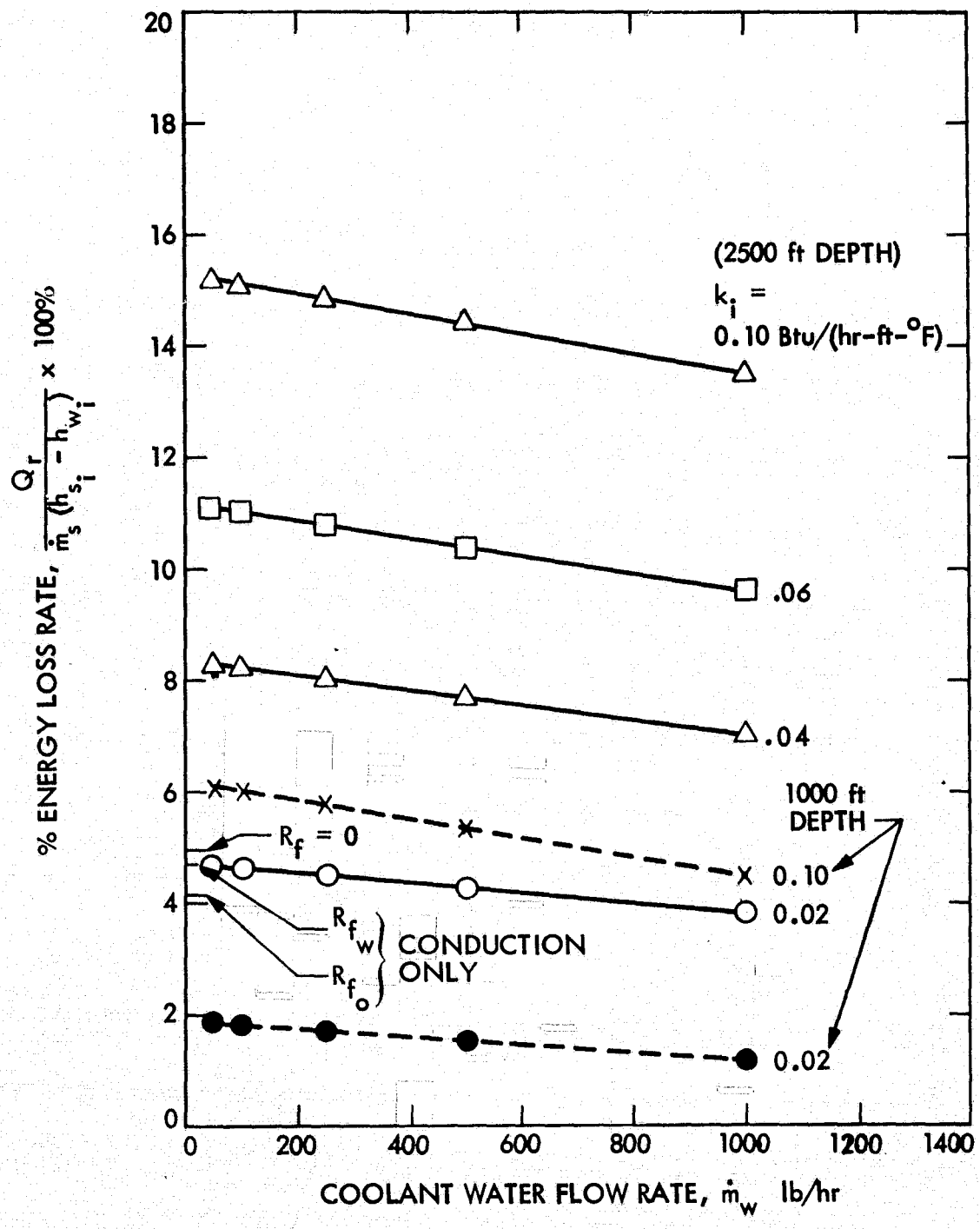

Figure E-4. Percent Energy Loss Rate to Surrounding Rock
t = 1 Week

Table E-1. Heat Transfer Rates for Well of Depth 2500 Ft; $\dot{m}_s + \dot{m}_w = 7250$ lb/hr, $Q_i = 7 \times 10^6$ BTU/hr, + = 1 Week

	k_i = 0.02 BTU/(hr-Ft-°F)				k_i = 0.04			
$\dot{m}_w$ lb/hr	Q_w, $\frac{BTU}{hr}$	Q_s	$\frac{Q_w}{Q_s}$	Q_r	Q_w	Q_s	$\frac{Q_w}{Q_s}$	Q_r
50	3,820	332,280	0.011	328,500	5,930	584,600	0.010	578,700
100	7,620	332,700	0.023	325,080	11,800	585,800	0.020	573,900
250	18,940	333,950	0.057	315,000	29,500	589,200	0.050	559,700
500	37,530	336,000	0.112	298,500	58,780	594,900	0.099	536,100
1,000	73,580	339,970	0.216	266,400	116,300	606,000	0.192	489,700

	k_i = 0.06				k_i = 0.10			
$\dot{m}_w$ lb/hr	Q_w	Q_s	$\frac{Q_w}{Q_s}$	Q_r	Q_w	Q_s	$\frac{Q_w}{Q_s}$	Q_r
50	7,590	782,800	0.010	775,200	10,000	1,074,000	0.009	1,064,000
100	15,200	784,800	0.019	769,600	20,000	1,077,600	0.019	1,058,000
50	37,800	790,600	0.048	752,800	50,000	1,088,000	0.046	1,038,000
500	75,400	800,400	0.094	725,000	99,900	1,106,000	0.090	1,006,000
1,000	149,900	819,700	0.183	669,800	199,000	1,141,000	0.174	942,200

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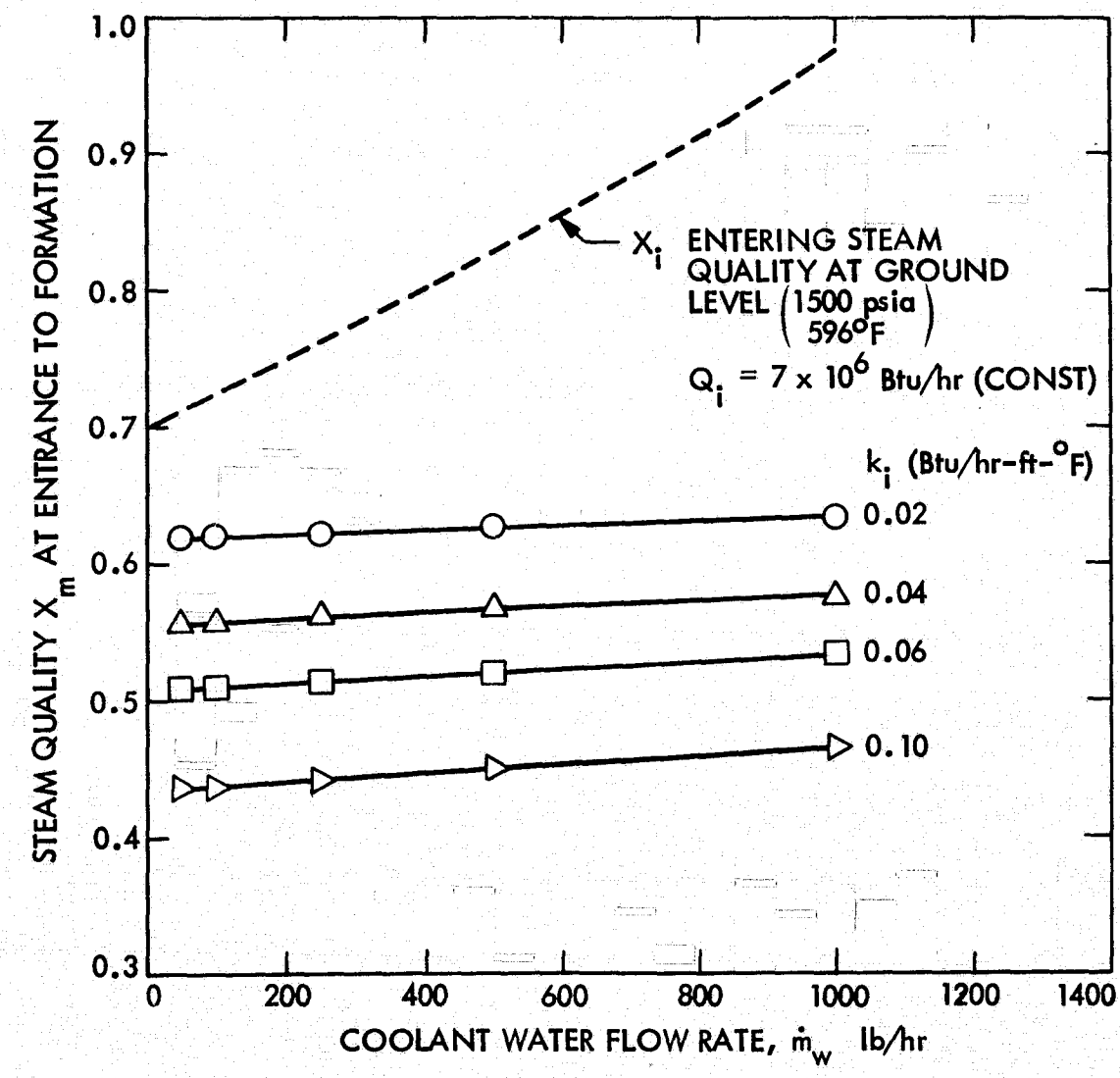

Figure E-5. Steam Quality at Entrance to Formation: L = 2500 ft, t = 1 Week

D. OTHER CONSIDERATIONS

1. No Forced Flow in Annulus

If there is no forced flow through the annulus there is not much basis to estimate the thermal resistance of the fluid in the annulus with certainty when the Rayleigh number exceeds a certain value. The Rayleigh number, a product of the Grashof and Prandtl numbers,

$$Ra = Gr\ Pr = \frac{g\beta b^3 \Delta T}{\nu_f \alpha_f} \tag{24}$$

depends upon the width of the annulus $b = r_2 - r_i$ cubed, the temperature difference between the outside of the insulation and the casing $\Delta T = T_i - T_c$, the gravitational force per unit mass, and fluid properties, β the coefficient of volume expansion, ν_f the kinematic viscosity and α_f the thermal diffusivity. When the Rayleigh number is less than about 1000, heat transfer is by conduction (Ref. E-6). For Rayleigh numbers greater than about 1000 the higher temperature fluid near the insulation moves upward because of buoyant forces and the cooler fluid near the casing moves downward (Ref. E-6). In this natural convection regime the conductive heat transfer across the annulus is augmented by convection effects and the thermal resistance of the fluid in the annulus decreases below the conductive value. In addition, besides conduction and convection, radiative heat transfer occurs across the annulus with transparent fluids.

The major deterrent to calculation of the thermal resistance of the fluid in the annulus is that there is little information on natural convection in annuli with the large ratios of L/d_h typical of steam injection wells, e.g., for the previous calculations, $d_h = d_2 - d_i = 1.90$ in., so that for a 2500 Ft well, $L/d_h = 15{,}800$. Natural convection heat transfer measurements in vertical enclosures (Refs. E-7-9) have been limited to values of L/b up to only about 40 for which the heat transfer coefficient has been found to depend upon the value of L/b, tending to decrease with increasing L/b, although another experimental investigation (Ref. E-10) indicated virtually no change over the small range of L/b from 4 to 17 studied. There is really no basis for using information from such investigations in calculations for steam injection wells where values of L/d_h are so large.

In spite of the uncertainty in determining the thermal resistance of the fluid in the annulus, limiting cases can be evaluated to estimate the heat loss to the surrounding rock with no forced flow in the annulus. This analysis is presented in the following.

An energy balance on an elemental length dL of the steam tubing is given by

$$dQ_s = -\dot{m}_s dh_s = 2\pi r_1 U_1 (T_s - T_h) dL \tag{25}$$

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where the overall heat transfer coefficient, neglecting the thermal resistances of the condensing steam and metal tube and casing as before, is

$$U_1 = \frac{1}{\frac{r_1}{k_i} \ln \frac{r_i}{r_{10}} + R_f + \frac{r_1}{k_c} \ln \frac{r_h}{r_{20}}} \tag{26}$$

In this relation the thermal resistances to heat transfer are, respectively, the insulation resistance, the annular fluid resistance R_f, and the cement resistance. The total heat transfer to the surrounding rock is obtained by integration of equation 25.

$$Q_r = Q_s = 2\pi r_1 \int_o^L U_1 (T_s - T_h) dL = \dot{m}_s (h_{s_i} - h_s) \tag{27}$$

Relating the differential heat transfer rate dQ_s from equation 25 to that to the surrounding rock by the Ramey formulation (equation 6) gives the temperature of the outside of the cement as

$$T_h = \frac{f\, T_s + \frac{k_e}{r_1 U_1} T_e}{f + \frac{k_e}{r_1 U_1}} \tag{28}$$

which upon substitution in equation 27 completes the formulation.

Calculations were carried out for a steam flow rate $\dot{m}_s$ = 7250 lb/hr for the same conditions as considered previously, and for the low thermal conductivity insulation k_i = 0.02 BTU/hr-Ft-°F) since heat losses were minimal with it. The limiting values of the annular fluid resistance were taken to be associated with conduction alone, i.e., the maximum resistance

$$R_f = \frac{r_1}{k_f} \ln \frac{r_2}{r_i} \tag{29}$$

and a zero resistance for which the energy loss rate would be greatest.

For a 2500 Ft deep well the percent energy loss rate calculated for $R_f = 0$ was slightly less than 5% (see Figure E-4). If water were in the annulus and the heat transfer were solely by conduction R_{fw}, there would only be a slight decrease in the percent energy loss rate from the zero annular fluid resistance value as shown in Figure E-4, making the uncertainty in calculating the annular resistance trivial in this case. Since oil is a relatively poor thermal conductor $k_o \approx 0.08$ BTU/(hr-FT-°F) compared to water $k_w \approx 0.37$ BTU/(hr-Ft-°F), another calculation was made for a case where the annulus was filled with oil R_{fo} as indicated in Figure E-4. In this case, the calculated percent energy loss rate was slightly above 4%. Of note is that for both the calculations for water and oil the estimated Rayleigh numbers exceeded 1000 so that the thermal resistances for the annular fluid would be less than for conduction alone, and correspondingly, the percent heat loss would be higher than the minimum values shown in Figure E-4 labeled R_{fw} and R_{fo}.

2. Concentric Steam Tubing - Insulation Protection

To prevent compression of sealed low thermal conductivity fiberous or foam insulation materials by high pressures in the annulus either with or without coolant water flow, double tubing should be considered, i.e., the outside of the insulation should be protected by a concentric tube. Since the thermal resistance of the concentric metal tube would be negligible compared to the thermal resistance of the insulation, the preceding analysis would also be applicable, although the calculations would be slightly different because the water flow film side heat transfer coefficients would be larger because the hydraulic diameter would be smaller. For example, if a 5 in. diameter tube were used (OD = 5.00 in.; ID = 4.56 in.) the hydraulic diameter of the annulus $d_h = 6.276 - 5.00 = 1.276$ in., compared to a value of $d_h = 6.276 - 4.375 = 1.90$ in. without the concentric tube. The results of the calculation are shown in Figure E-6 which indicates only a slight increase in the percent energy loss rate. At junctions between the insulated concentric tube sections, semi-rigid insulation should be placed around the inner coupling between the pipe sections to minimize heat leak.

3. Smaller Steam Tubing - Thicker Insulation

Calculations of pressure drop in two phase steam flow (Appendix F) indicated that even though steam pressures would be about 100 psi lower at the well bottom with a smaller 1.9 in. tube ($d_{1O} = 1.90$; $d_1 = 1.61$ in.) than a 2-7/8 in. tube, they would still be on the order of the steam pressure of 1500 psia at ground level because of gravitational increases. This calculation indicated that there may be some merit in using a smaller diameter tube for which the thickness of insulation would be larger to reduce heat losses. For example, if a 5 in. diameter concentric tube to protect the insulation were used with a smaller 1.9 in. steam tube, the radial gap between the tubes would be 1.33 in. If 1-1/4 in. of insulation were placed in this gap, the calculated percent energy loss rate is shown in Figure E-6 compared to that for the 3/4 in. thick insulation. The reduction in energy loss would amount to about 50%.

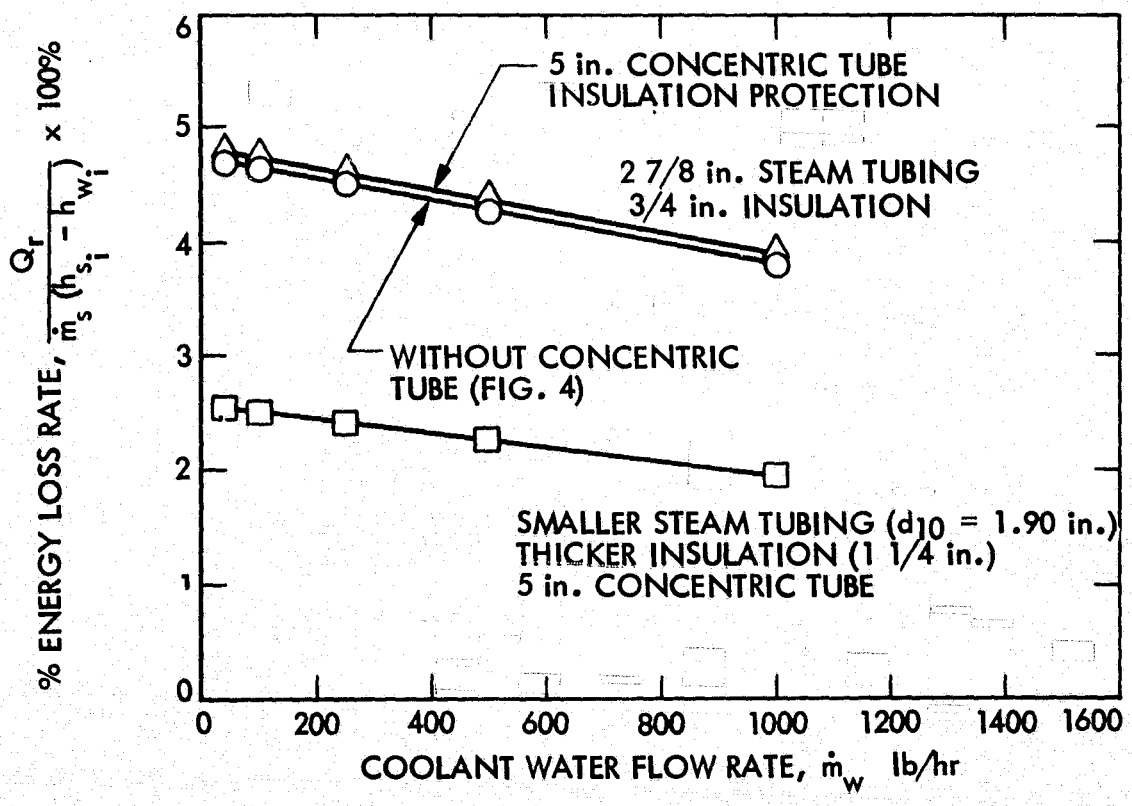

Figure E-6. Percent Energy Loss Rate to Surrounding Rock, for Various Conditions; k_i = 0.02 BTU/(hr-ft-°F), L = 2500 ft, t = 1 Week

4. No Insulation - Steam Flow Through Casing

To place the present calculations in perspective and to evaluate a situation used in practice in some injection wells, a calculation was made for steam injection directly through the casing, i.e., without an insulated steam pipe. For the same casing, cement and entering steam conditions as considered previously and a steam flow rate of 7250 lb/hr for one week, the percent energy loss rate would be 20% at a depth of 1000 Ft, and at a depth of 2000 Ft where the energy loss rate would be 40%, all of the steam would have condensed. For this situation the percent energy loss would greatly exceed those values shown in Figure E-4 for an insulated steam pipe, and hot water rather than wet steam would enter the formation at a depth of 2500 Ft.

5. Effect of Injection Period

The prior calculations were made for injection of steam and water for one week [f(T) = 2.27]. For injections for longer periods of time the surrounding rock increases in temperature, thereby decreasing the heat loss to the rock. To indicate the effect of longer injection periods, calculations were carried out for 30 and 180 days, f = 3.0 and 3.89 respectively, and are shown in Figure E-7. For the lower thermal conductivity insulation (k_i = 0.02 BTU/(hr-ft-°F)) the heat loss after 7 days is reduced by less than 10% when the time is extended to 180 days. Table E-2 gives the corresponding loss rates without insulation; the reductions with increasing time are greater.

E. FINDINGS

The calculations have indicated that tubing insulation is very important in reducing heat losses and casing temperatures, and should be used in steam injection wells. Low thermal conductivity insulation materials with k_i on the order of 0.02 BTU/(hr-Ft-°F) are recommended. To prevent compression of such fibrous or foam insulation materials by high pressures in the annulus, double tubing should be considered, i.e., the outside of the insulation should be protected by a concentric tube. Smaller steam tubing for which thicker insulation could be used would further reduce the energy losses. Some of the calculated values are listed in Table E-2.

Forced coolant water flow in the annulus between the tubing insulation and casing was found to decrease the heat losses to the surrounding rock and reduce the casing temperatures. To avoid using too high quality entering steam and associated heater scaling problems, smaller coolant water flow rates are recommended. Use of coolant water flow through the annulus would obviate the need for a packer and prevent intrusion of steam into the annulus at the well bottom as occurs when packings fail because of high steam temperatures.

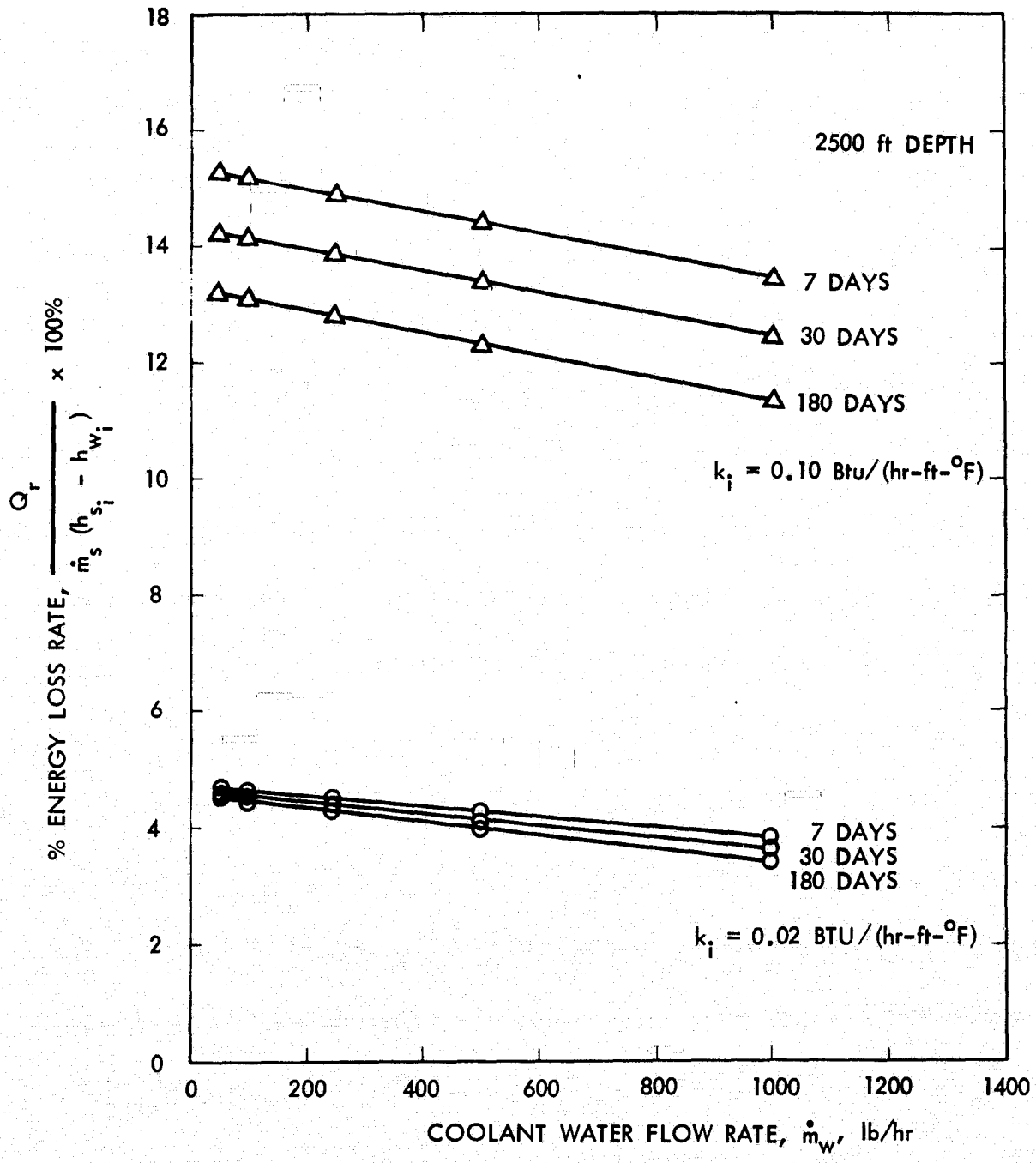

Figure E-7. Effect of Injection Period on Percent Energy Loss Rate to Surrounding Rock

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Table E-2. Thermal Characteristics for Various Injection Well Conditions
$\dot{m}_s + \dot{m}_w$ = 7250 lb/hr, k_i = 0.02 BTU/(hr-ft-°F), t = 1 week

Steam Tubing O.D., d_{10} in.	Insulation Thickness in.	Concentric Tube O.D. in.	Annulus Fluid	Coolant Flow Rate, $\dot{m}_w$ lb/hr	Annulus Resistance R_f	Energy Loss Rate, %	Steam Quality at Entrance to Formation, X_m %	Maximum Casing Temperature, T_{cm} °F
L = 2500 ft, p_i = 1500 psia, T_{s_i} = 596°F, Q_i = 7 x 10^6 BTU/hr								
Injection time t = 7 days								
None	None	None	None	None	None	~50	0	~596
2-7/8 or 1.9	None	None	-	0	0	50	0	583
2-7/8	None	None	Water	0	Cond.*	26	25	348
1.9	None	None	Water	0	Cond.*	20	35	287
2-7/8	None	None	Oil	0	Cond.*	10	53	185
2-7/8	3/4	None	-	0	0	5.0	62	140
2-7/8	3/4	None	Water	0	Cond.*	4.8	62	138
2-7/8	3/4	5	Water	0	Cond.*	4.8	62	138
2-7/8	3/4	5	Water	250	-	4.6	62	138
2-7/8	3/4	None	Water	250	-	4.5	62	137
2-7/8	3/4	5	Water	500	-	4.4	62	137
1.9	1-1/4	5	Water	250	-	2.4	66	119
1.9	1-1/4	5	Water	500	-	2.3	66	115

*Heat transfer solely by conduction.

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Table E-2. Thermal Characteristics for Various Injection Well Conditions (Contd)

Steam Tubing O.D., d_{10} in.	Insulation Thickness in.	Concentric Tube O.D. in.	Annulus Fluid	Coolant Flow Rate, $\dot{m}_w$ lb/hr	Annulus Resistance R_f	Energy Loss Rate, %	Steam Quality at Entrance to Formation, X_m %	Maximum Casing Temperature, T_{cm} °F
Injection time t = 30 days								
None	None	None	None	None	None	41	0	~596
2-7/8	None	None	-	0	0	41	0	585
2-7/8	None	None	Water	0	Cond.*	23	29	374
2-7/8	3/4	None	Water	250	-	4.4	62	146
Injection time t = 180 days								
None	None	None	None	None	None	33	12	~596
2-7/8	None	None	-	0	0	33	12	587
2-7/8	None	None	Water	0	Cond.*	21	34	400
2-7/8	3/4	None	Water	250	-	4.3	63	158

*Heat transfer solely by conduction.

Table E-2. Thermal Characteristics for Various Injection Well Conditions (Contd)

Steam Tubing O.D., d_{10} in.	Insulation Thickness in.	Concentric Tube O.D. in.	Annulus Fluid	Coolant Flow Rate, $\dot{m}_w$ lb/hr	Annulus Resistance R_f	Energy Loss Rate, %	Steam Quality at Entrance to Formation, X_m %	Maximum Casing Temperature, Tc_m °F
		L = 1000 ft, p_i = 500 psia, T_{s_i} = 467°F, Q_i = 6.8 x 10^6 BTU/hr						
None	None	None	None	None	None	16	51	467
2-7/8	None	None	-	0	0	16	51	~460
2-7/8	None	None	Water	0	Cond.*	8.2	60	277
2-7/8	None	None	Oil	0	Cond.*	3.0	66	151
2-7/8	3/4	None	-	0	0	1.6	68	116
2-7/8	3/4	None	Water	0	Cond.*	1.5	68	114
2-7/8	3/4	None	Oil	0	Cond.*	1.3	68	110
2-7/8	3/4	None	Water	50	-	1.5	68	114
2-7/8	3/4	None	Water	250	-	1.3	68	114

*Heat transfer solely by conduction.

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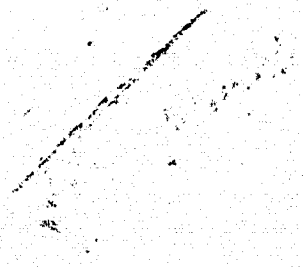
NOMENCLATURE

c_{p_w}	Specific heat of water
d	diameter (same subscripts as for radius)
d_h	hydraulic diameter, $d_2 - d_i$
f	Weishbach friction factor
f(T)	Ramey function
g	gravitational force per unit mass
g_c	conversion constant
G	mass flux of steam
h_m	mixture enthalpy defined in eq. 19
h_w	enthalpy of water
hw_i	enthalpy of water at surface
h_s	enthalpy of steam
hs_i	enthalpy of steam at surface
h_{fg}	latent heat of vaporization
h_{c_s}	heat transfer coefficient for condensing steam
h_c	water side heat transfer coefficient
k_t	thermal conductivity of tubing
k_i	thermal conductivity of insulation
k_w	thermal conductivity of water
k_2	thermal conductivity of casing
k_c	thermal conductivity of cement
k_e	thermal conductivity of surrounding rock
L	depth below surface
$\dot{m}_s$	mass flow rate of steam

$\dot{m}_w$	mass flow rate of water
p	Pressure
p_i	pressure at surface
Q_i	energy rate to produce steam from water
Q_r	heat transfer rate to surrounding rock
Q_s	heat transfer rate from the steam flow
Q_w	heat transfer rate to the water coolant
r_1	inside radius of steam tubing
r_{10}	outside radius of steam tubing
r_i	outside radius of insulation
r_2	inside radius of casing
r_{20}	outside radius of casing
r_h	outside radius of cement
Ra	Rayleigh number
R_f	thermal resistance of fluid in annulus
t	time
T_c	temperature of casing
T_e	temperature of rock
T_g	surface geothermal temperature
T_h	outside temperature of cement
T_s	temperature of steam
T_w	water temperature
Tw_i	entering water temperature
u	water velocity
U_1	overall heat transfer coefficient with no forced flow in annulus
U_i	overall heat transfer coefficient on inside of the annulus

U_2	overall heat transfer coefficient on the outside of the annulus
v	specific volume of steam
W_w	specific weight of water
α_e	thermal diffusivity of rock
β	function defined in eq. 10 or coefficient of volume expansion, eq. 24
γ	function defined in eq. 11
ν_w	kinematic viscosity of water
ξ	function defined in eq. 8
ρ	density
T	dimensionless time, $\frac{\alpha_e t}{r_h^2}$
χ_m	steam quality at entrance to formation



APPENDIX F

PRESSURE VARIATION WITH DEPTH FOR STEAM FLOW

Lloyd H. Back

APPENDIX F

PRESSURE VARIATION WITH DEPTH FOR STEAM FLOW

Application of the momentum equation gives the variation of pressure with depth as

$$p - p_1 = \Delta p_g - \Delta p_f + \Delta p_m$$

In this relation Δp_g is the increase in pressure due to gravity

$$\Delta p_g = \overline{\rho} \frac{g}{g_c} L$$

Δp_f is the frictional pressure drop

$$\Delta p_f = \left(\frac{\overline{f}L}{d_1}\right)\left(\frac{G^2\overline{v}}{2g_c}\right)$$

and Δp_m is the pressure change due to momentum changes.

$$\Delta p_m = \frac{G^2}{g_c}(v_i - v)$$

In these expressions f is the Weishbach friction factor, G is the steam mass flux, v is the specific volume of steam and the barred quantities are average values for the depth of the well.

Calculations were carried out for a flow rate $\dot{m}_s$ = 7250 lb/hr of initial 70% quality steam at a pressure of p_i = 1500 psia and saturation temperature of T_{si} = 596°F for a 2-7/8 in. tube (d_1 = 2.441 in.) by using the method of Thom as described in Reference F-1 for the two phase mixture of steam and water. The frictional pressure drop was estimated for adiabatic flow since there is little information on condensing steam flows inside tubes. For a well of depth 2500 ft the calculations indicated a frictional pressure drop of about 15 psi, a gravitational pressure increase of about 100 psi, and a negligible pressure change (a small fraction of a psi) associated with momentum changes. The estimated pressure at the well bottom was 1585 psia for which the saturation temperature would be 604°F, a value not much different from the entering steam temperature of 596°F. The estimated vapor velocity was only 13 ft/sec.

An estimate was made of the frictional pressure drop for a smaller 1.9 in. tube (d_1 = 1.61 in.) for the same steam flow rate. The estimated frictional pressure drop was about 115 psi, a value 100 psi higher than for the 2-7/8 in. tube, and the estimated pressure at the well bottom was 1485 psia.

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NOMENCLATURE

See Appendix E.

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APPENDIX G

HEAT LOSSES AT STEAM TUBING COUPLING REGIONS

Lloyd H. Back

APPENDIX G

HEAT LOSSES AT STEAM TUBING COUPLING REGIONS

An approximate thermal analysis was carried out to estimate the additional heat loss at tubing coupling regions with the insulation protected by concentric pipe. In this case there is a fin effect at the end plate and increased heat transfer in the vicinity of the coupling region. A detailed view of part of the coupling region is shown in Figure G-1. At the end of each section of pre-fabricated tubing, the end plate, welded to the steam tubing and concentric pipe, allows heat to be conducted from the steam flow to the concentric pipe. There is heat conduction longitudinally along the concentric pipe from which heat transfer occurs radially by convection to the coolant water flow. The concentric pipe also receives heat conducted radially through the steam tubing insulation.

An energy balance on an incremental length dx of the concentric pipe in the longitudinal x direction (Figure G-1) is given by

$$- \frac{d\, q_x}{dx} A_1 + q_{r_i} (2\pi r_b) - q_{r_o} (2\pi r_{bo}) = 0 \tag{1}$$

where the longitudinal and radial heat fluxes are

$$q_x = -k \frac{dT}{dx} \tag{2}$$

$$q_{r_i} = \frac{k_i (T_{10} - T)}{r_b \ln \frac{r_b}{r_{10}}} \tag{3}$$

$$q_{r_o} = h_o (T - T_w) \tag{4}$$

and A_1 is the cross sectional area of the concentric pipe

$$A_1 = \pi (r_{bo}^2 - r_b^2) \tag{5}$$

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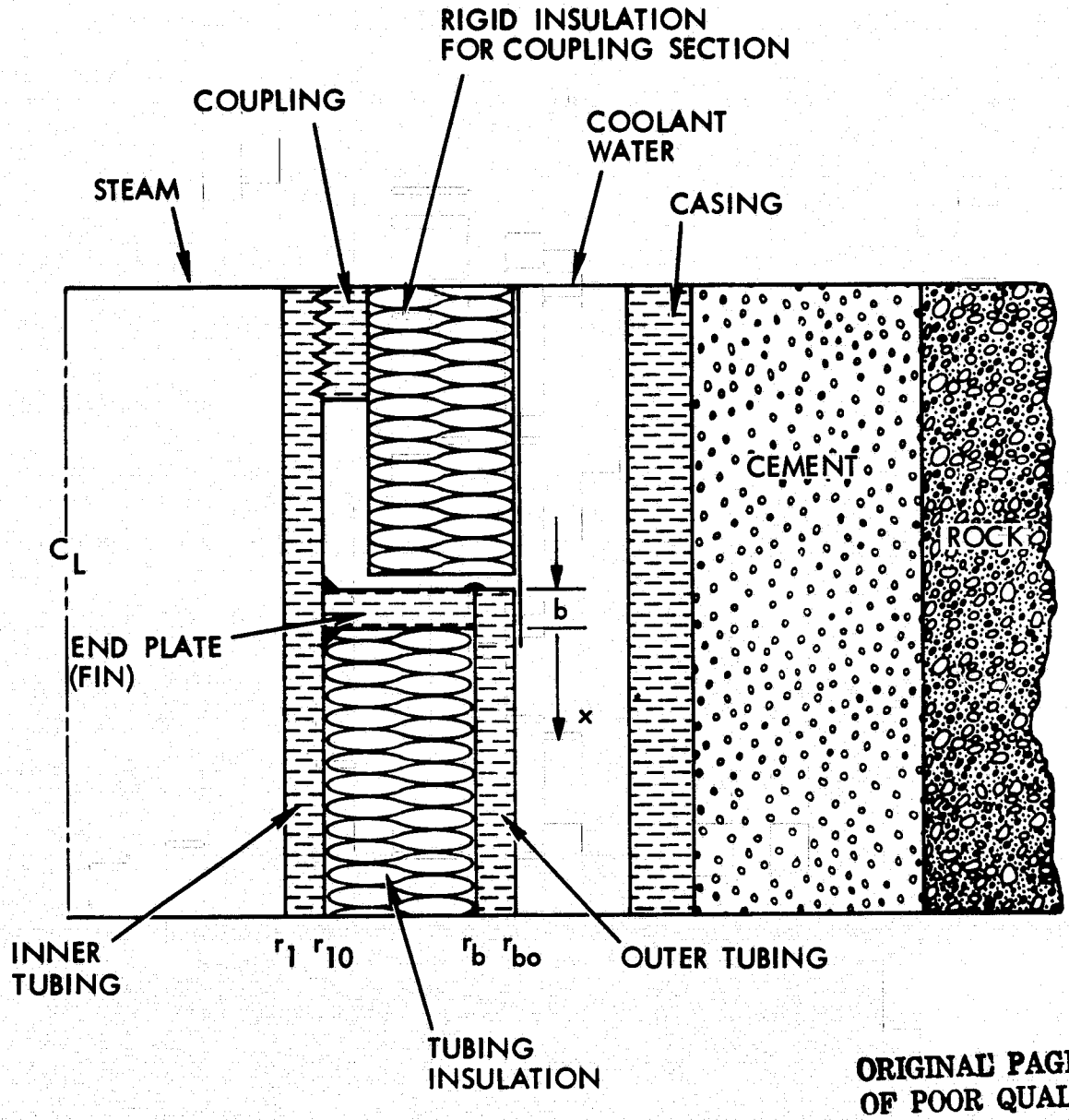

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Figure G-1. Lower Part of Tubing Coupling Region

The local temperature T, the average value across the concentric pipe wall, is dependent upon x as given by the second order differential equation obtained by substituting equations 2, 3 and 4 into eq. 1.

$$kA_1\frac{d^2T}{dx^2} + \frac{2\pi k_i\,(T_{10}-T)}{\ell n\,\frac{r_b}{r_{10}}} - 2\pi r_{bo}h_o\,(T-T_w) = 0 \tag{6}$$

It is convenient to introduce the dimensionless temperature difference ratio

$$\phi = \frac{T-T_w}{T_{10}-T_w} \tag{7}$$

where T_w is the water temperature and T_{10} is the steam pipe temperature so that eq. 6 becomes

$$\frac{d^2\phi}{dx^2} - m^2\phi + n = 0 \tag{8}$$

where $$m = \left(\frac{2\,\pi k_i}{kA_1\,\ell n\,\frac{r_b}{r_{10}}} + \frac{2\,\pi r_{bo}h_o}{kA_1}\right)^{1/2} \tag{9}$$

and $$n = \frac{2\,\pi k_i}{kA_1\,\ell n\,\frac{r_b}{r_{10}}} \tag{10}$$

To the order of this analysis, longitudinal variation in the water temperature is neglected compared to the variation in the temperature T of the concentric pipe wall. This turns out to be a good assumption as will be seen subsequently.

The boundary conditions are that at the end plate

$$x = o;\ T = T_{bo} \quad \text{or} \quad \phi = \frac{T_{bo}-T_w}{T_{10}-T_w} = \phi_o \tag{11}$$

and from the end plate

$$x \to \frac{\ell}{2} \; ; \; T \to \overline{T}_b \quad \text{or} \quad \phi \to \frac{\overline{T}_b - T_w}{T_{10} - T_w} = \phi_b \tag{12}$$

In these expressions T_{bo} is the temperature of the base of the concentric pipe (the outer edge of the end plate) and $\overline{T}_b$ is the temperature at 1/2 the length ℓ of the tubing section which is essentially the value without the fin effect that was previously calculated in Appendix E. The other one-half of the tubing section has an end plate at the other end so that the thermal analysis is symmetric about $\ell/2$.

The solution of eq. 8 is given by

$$\phi = (\phi_o - \phi_b)\, e^{-mx} + \phi_b \tag{13}$$

where $$\phi_b = \frac{n}{m^2} \tag{14}$$

is the dimensionless temperature difference ratio that would occur without the fin effect.

The temperature T_{bo} at the outer edge of the end plate is related to the radial heat conduction in the end plate. This relationship is obtained by equating the heat conduction into the base of the concentric tube at $x = o$ to the radial heat conduction in the end plate. The heat conduction into the base of the concentric tube is

$$Q_b = -A_1 k \left(\frac{dT}{dx}\right)_{x=o} = -A_1 k\, (T_{10} - T_w) \left(\frac{d\phi}{dx}\right)_{x=o} = A_1 k\, (T_{10} - T_w)(\phi_o - \phi_b) m \tag{15}$$

where the third equality follows by differentiating eq. 13. The radial conduction in the end plate which is insulated on each side is given by

$$Q_e = \frac{2\pi kb\, (T_{10} - T_{bo})}{\ell n \, \frac{r_b}{r_{10}}} = \frac{2\pi kb\, (T_{10} - T_w)\, (1 - \phi_o)}{\ell n \, \frac{r_b}{r_{10}}} \tag{16}$$

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Equating these two expressions,

$$Q_b = Q_e \tag{17}$$

and solving for the temperature T_{bo} via ϕ_o gives

$$\phi_o = \frac{1 + \frac{A_1 m}{2\pi b} \ln \frac{r_b}{r_{10}} \phi_b}{1 + \frac{A_1 m}{2\pi b} \ln \frac{r_b}{r_{10}}} \tag{18}$$

Once the temperature distribution along the concentric tube is known i.e. $T(x)$ or $\phi(x)$, the heat transfer to the water in the annulus can be determined from

$$Q_{ro} = \int_o^{\ell/2} q_{r_o} (2\pi r_{bo}) \, dx = 2\pi r_{bo} h_o \int_o^{\ell/2} (T - T_w) \, dx = 2\pi r_{bo} h_o (T_{10} - T_w) \int_o^{\ell/2} \phi dx \tag{19}$$

Without the fin effect, the corresponding heat transfer to the water in the annulus is

$$Q_{ro_n} = 2\pi r_{bo} h_o \int_o^{\ell/2} (\overline{T}_b - T_w) \, dx = 2\pi r_{bo} h_o (T_{10} - T_w) \, \phi_b \, \frac{\ell}{2} \tag{20}$$

By carrying out the integration in eq. 19 with ϕ given by eq. 13, the ratio of heat transfer with the fin effect to that without the fin effect is given by

$$\frac{Q_{ro}}{Q_{ro_n}} = 1 + \left\{ \left(\frac{\phi_o}{\phi_b} - 1 \right) \frac{(1 - e^{-m\frac{\ell}{2}})}{m \frac{\ell}{2}} \right\} \tag{21}$$

Application

Calculations were carried out for 2-7/8 in. steam tubing (d_{10} = 2.875 in; d_1 = 2.441 in.) and 5 in. concentric pipe (d_{bo} = 5.00 in; d_b = 4.56 in.) with 3/4 in. insulation with thermal conductivity k_i = 0.02 BTU/(hr-ft-°F) and coolant water flow rate, $\dot{m}_w$ = 250 lb/hr. The entering steam conditions of

1500 psia and 596 °F were the same as considered in Appendix E as also were the other well conditions. The thermal conductivity k of the steam pipe, end plate and concentric pipe was taken to be 27 BTU/(hr-ft-°F), the end plate thickness b was taken to be 0.25 in., and the length of the tubing section ℓ = 30 ft. The water side heat transfer coefficient was h_o = 13.2 BTU/(hr-ft^2-°F) and the temperature of the steam tubing T_{10} was approximated as the steam temperature. At a depth of 1000 ft. the calculated water temperature T_w = 133° F from Appendix E.

The calculated value of m from eq. 9 was 5.3 ft^{-1}, the temperature $\overline{T}_b$ = 140° F (ϕ_b = 0.0156) from eq. 14, and T_{bo} = 389° F (ϕ_o = 0.71) from eq. 18. The variation of the concentric pipe temperature in terms of ϕ is shown in Figure 2 (left side). Most of the temperature variation was in the short longitudinal distance of about 1 ft. for which the additional heat transfer defined as

$$\varepsilon = \frac{\int_o^x e^{-mx} dx}{\int_o^{\ell/2} e^{-mx} dx} = \frac{1 - e^{-mx}}{1 - e^{-m\ell/2}} \qquad (22)$$

occurred (Figure G-2, right side). For this situation the ratio of heat transfer with the fin effect to that without the fin effect Q_{ro}/Q_{ro_n} = 1.55 from eq. 21, or about 50% more. This ratio could be decreased by using a lower thermal conductivity end plate and short section of about 1 ft. of concentric pipe. For example, for k = 10 BTU/(hr-ft-°F) rather than 27 BTU/(hr-ft-°F), the ratio Q_{ro}/Q_{ro_n} = 1.28. If in addition the end plate were thinner, say b = 0.10 in. rather than 0.25 in., the ratio Q_{ro}/Q_{ro_n} = 1.17 or less than 20% more. Corresponding ratios for the 1.9 in. steam tubing are Q_{ro}/Q_{ro_n} = 1.83, 1.39 and 1.21 compared to the above values of 1.55, 1.28 and 1.17 for the 2-7/8 in. steam tubing. It appears that the additional heat loss due to the fin effect could be reduced by appropriate design.

A final estimate was made of the effect of using rigid insulation around the pipe coupling as depicted in Figure G-1. If the length of the coupling insulation is about 1 ft. and the tubing section length is 30 ft; then a weighted average can be used to estimate the additional heat loss associated with the higher thermal conductivity rigid insulation at the coupling compared

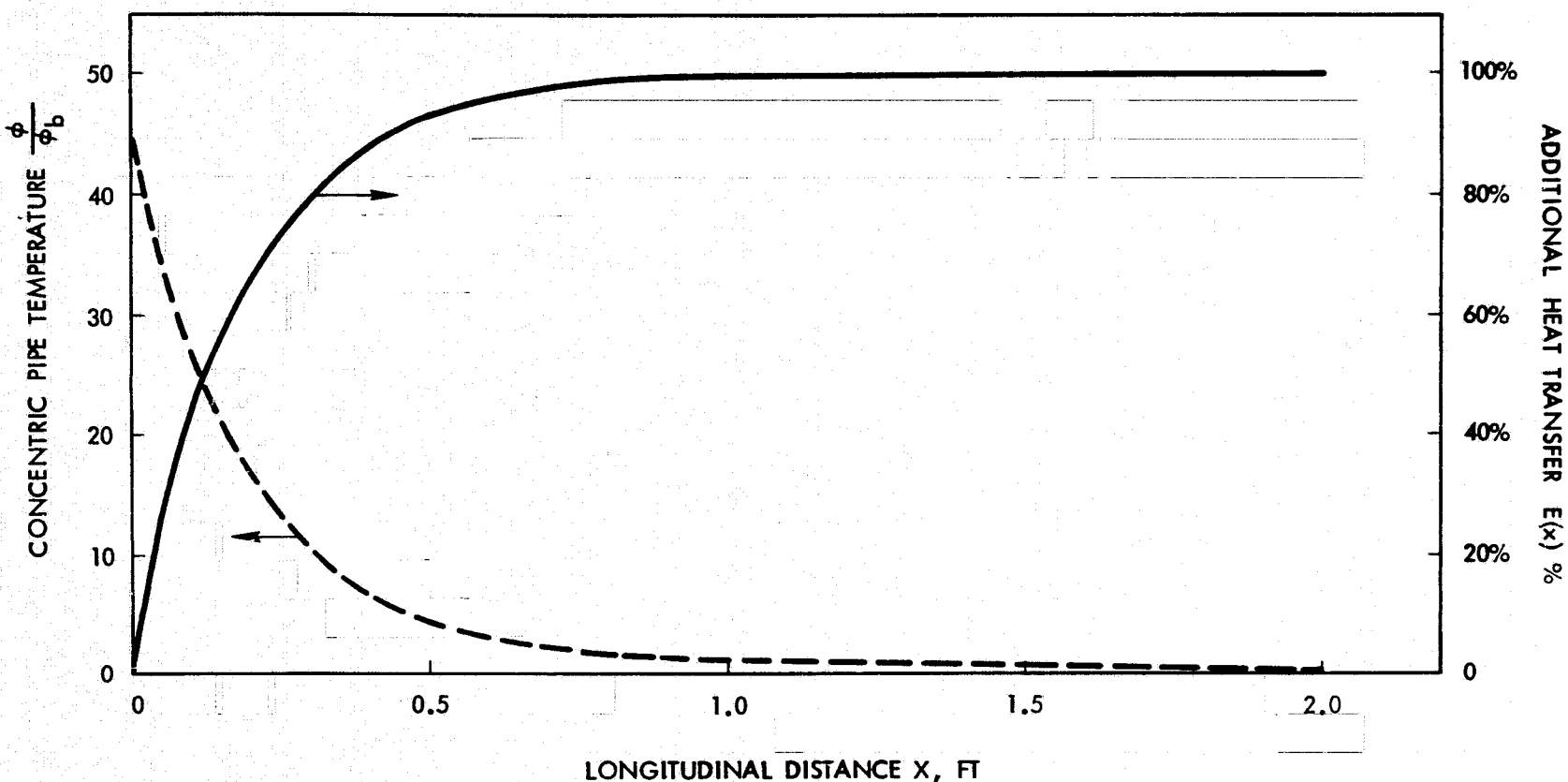

Figure G-2. Concentric Pipe Temperature and Additional Heat Transfer Variation in Longitudinal x Direction

to the lower thermal conductivity insulation between the steam tubing and concentric pipe. For example, for a thermal conductivity of 0.35 BTU/(hr-ft-°F) for the rigid material and 0.02 BTU/(hr-ft-°F) for the insulation between the steam and concentric tubing, the calculations in appendix E for a depth of 2500 ft. gives

$$R = \frac{\frac{1}{30}(26\%) + \frac{29}{30}(4.5\%)}{4.5\%} = 1.16$$

or a value of about 15% higher. A rough estimate of the effect of not using any insulation around the pipe coupling gives a value of

$$R \simeq \frac{\frac{1}{30}(40\%) + \frac{29}{30}(4.5\%)}{4.5\%} = 1.26$$

Corresponding ratios for the 1.9 in. steam tubing are R = 1.24 and 1.45 compared to the above values of 1.16 and 1.26 for the 2-7/8 in. steam tubing.

The total additional heat loss associated with the fin effect at the end plate and the higher thermal conductivity rigid insulation at the coupling can be estimated by adding together the calculated values. For example, for the 2-7/8 in. steam tubing, the total additional heat loss is estimated to be 17% plus 16% or about 1/3 higher for a lower conductivity end plate and short 1 ft. section of concentric pipe and thinner end plate. Thus, the values of the per cent energy loss rate calculated in Appendix E should be increased by about 1/3 in this case to account for additional heat losses at steam tubing coupling regions for insulation protection with the concentric pipe.

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APPENDIX H

SOLAR ENERGY FOR GENERATION OF INJECTION STEAM

William A. Owen

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APPENDIX H

SOLAR ENERGY FOR GENERATION OF INJECTION STEAM

Statement of Problem: Due to the viscous nature of the crude petroleum in the Bakersfield area, steam is injected into the wells to improve the flow characteristics of the crude by heating. Table H-1 shows typical operating conditions from which heat rates were calculated and listed in the last column. These were calculated by using the steam properties shown in Table H-2. From this data, two "typical" steam plants were extracted:

	Heat Rate	Temperature	Make Up Water
Plant 1	8.5×10^6 BTU/hr	600°F	600 bbl/Day
Plant 2	5×10^6	400	325

Various configurations of solar heating systems were then examined to determine if these plants would be economically viable, taking the Bakersfield, Ca., area as one in which solar heating might offer promise.

Problem Analysis: Weather data for Bakersfield were not readily available; however, data for Fresno were available. Since these cities are only about 100 miles apart and are in the same valley, this data seems adequate. The Climatological Atlas seems to confirm this assumption. The data for Fresno are shown in Table H-3. Note there are about nine good months (over 72% of possible sunshine) and three very poor ones. For a first try, an average insolation rate of 1700 BTU/ft^2·day was chosen.

For the temperatures required, the most economical solar collector currently under development is the parabolic trough with a linear receiver at the focus. Since this type collector has a limited angular acceptance aperture, it must track the sun throughout the day. While this increases the cost of the collectors, it does improve overall energy collection due to reduced cosine losses by about 35%. Therefore, a daily insolation rate for a tracking collector can be calculated:

$$1700 \text{ BTU/ft}^2\cdot\text{day} \times 1.35 = 2300 \text{ BTU/ft}^2\cdot\text{day}$$

Table H-1. Field Conditions for Steam Injection - Per Well

Case	Company	Water Flow bbl/day	Steam Quality %	P_{sig} Pressure	Installed Capacity	Heat Rate - Calc.
1	Getty	600	70	2000	6-12 x 10^6 BTU/Hr	8.37 x 10^6 BTU/Hr
				1500		8.42 x 10^6
2	Chanslor-Western	250	(assume 80)	150	-	3.59 x 10^6
3	Texaco	580	80	240*	13 x 10^6	8.42 x 10^6
				190*		8.37 x 10^6
4	Getty	300 - 350	60	800	-	4.19 x 10^6
		325	70			4.52 x 10^6
5	Berry	330	80	450	7 x 10^6	4.87 x 10^6
				250		4.81 x 10^6

* psia

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Table H-2. Steam Conditions

P_{psia}	$T_{SAT}{}^{o}F$	hg $\frac{BTU}{lb}$	hf $\frac{BTU}{lb}$	v_g $\frac{ft^2}{lb}$	v_f $\frac{ft^3}{lb}$	Q %	ρ lb/ft^3	ΔH $\frac{BTU}{lb}$*
2000	635.82	1135.1	671.7	0.1878	.0257	70	7.1855	958.08
1500	596.23	1167.9	611.6	0.2765	.0235	70	4.9850	962.87
						60	2.8606	885.04
800	518.23	1198.6	509.7	0.5687	.0209	70	2.4730	953.93
460	458.50	1204.6	439.7	1.0094	.0196	80	1.2324	1013.62
265	406.11	1201.7	381.6	1.7422	.01873	80	0.7156	999.68
240	397.37	1200.6	372.12	1.9183	.01860	80	0.6500	996.90
190	377.51	1197.6	350.79	2.404	.01833	80	0.5190	990.24
164	365.51	1195.5	338.02	2.768	.01818	80	0.4508	986.00

* ΔH assumes water enters at $70^{o}F$ and 1 atm (H = 38 BTU/lb)

Table H-3. Sunshine at Fresno 36° 41'N 119° 47'W

	Hours of Possible Sunshine (15th) Hrs	Min	Mean Hrs. of Sunshine	% Possible Sunshine	Mean Daily Solar Rad. Langleys	kW·Hrs/m^2	BTU/ft^2·day
Jan	10	04	153	46	184	2.1385	677.90
Feb	10	57	192	63	289	3.3588	1064.75
Mar	11	56	283	72	427	4.9627	1573.17
Apr	13	04	330	83	552	6.4155	2033.70
May	13	59	389	89	647	7.5196	2383.71
Jun	14	30	418	94	702	8.1588	2586.34
Jul	14	17	435	97	682	7.9264	2512.66
Aug	13	29	406	97	621	7.2174	2287.92
Sep	12	24	355	93	510	5.9273	1878.97
Oct	11	20	306	87	376	4.3700	1385.28
Nov	10	21	221	73	250	2.9056	921.06
Dec	9	50	144	47	161	1.8712	593.16
Annual			3632		450		1658.22

The efficiency of this type of collector varies as shown in Figure H-1. For Plant 1, the efficiency at 600°F is about 60%. The required aperture area is then:

$$\frac{8.5 \times 10^6 \text{ BTU/hr} \times 24 \text{ hr/day}}{2300 \text{ BTU/ft}^2\cdot\text{day} \times 0.60} \simeq 150{,}000 \text{ ft}^2$$

The cost of such a collector is currently about $\$18/\text{ft}^2$ from Figure H-2, therefore:

$$150{,}000 \text{ ft}^2 \times \$18/\text{ft}^2 = \$2.70 \text{ million}$$

Note, however, that while this collector system accepts the entire required heat load, it does it in daylight hours only, so storage is required for the night. If we assume half the energy is stored during the day for use at night, the amount stored is:

$$8.5 \times 10^6 \text{ BTU/hr} \times 12 \text{ hr} \cong 1 \times 10^8 \text{ BTU}$$

$$1 \times 10^8 \text{ BTU} \times 2.93 \times 10^{-4} \frac{\text{kW}\cdot\text{hr}}{\text{BTU}} \simeq 30{,}000 \text{ kW}\cdot\text{hr}$$

Current costs of storage for electric plants is about $\$75/\text{kW}\cdot\text{hr}$. If we assume the plant to be about 50% efficient in converting heat to electricity, then thermal storage should be about $37.50/\text{kW}\cdot\text{hr}$ thermal. The cost of storage is then:

$$30{,}000 \times \$37.50 \cong \$1.12 \text{ million}$$

and the total plant investment:

$$2.70 + 1.12 = \$3.82 \text{ million}$$

Plant 2 was checked to see if the higher efficiency was of any significance, thus:

$$\frac{5.0 \times 10^6 \text{ BTU/hr} \times 24 \text{ hr/day}}{2300 \text{ BTU/ft}^2\cdot\text{day} \times 0.65} \simeq 80{,}000 \text{ ft}^2$$

$$80{,}000 \text{ ft}^2 \times \$18/\text{ft}^2 = \$1.44 \times 10^6$$

Storage: $5 \times 10^6 \text{ BTU/hr} \times 12 \text{ hr} \times 2.93 = 17{,}600 \text{ kW}\cdot\text{hr}$

$$17{,}600 \times 37.50 = \$660{,}000$$

$$1{,}440{,}000 + 660{,}000 = \$2.10 \times 10^6$$

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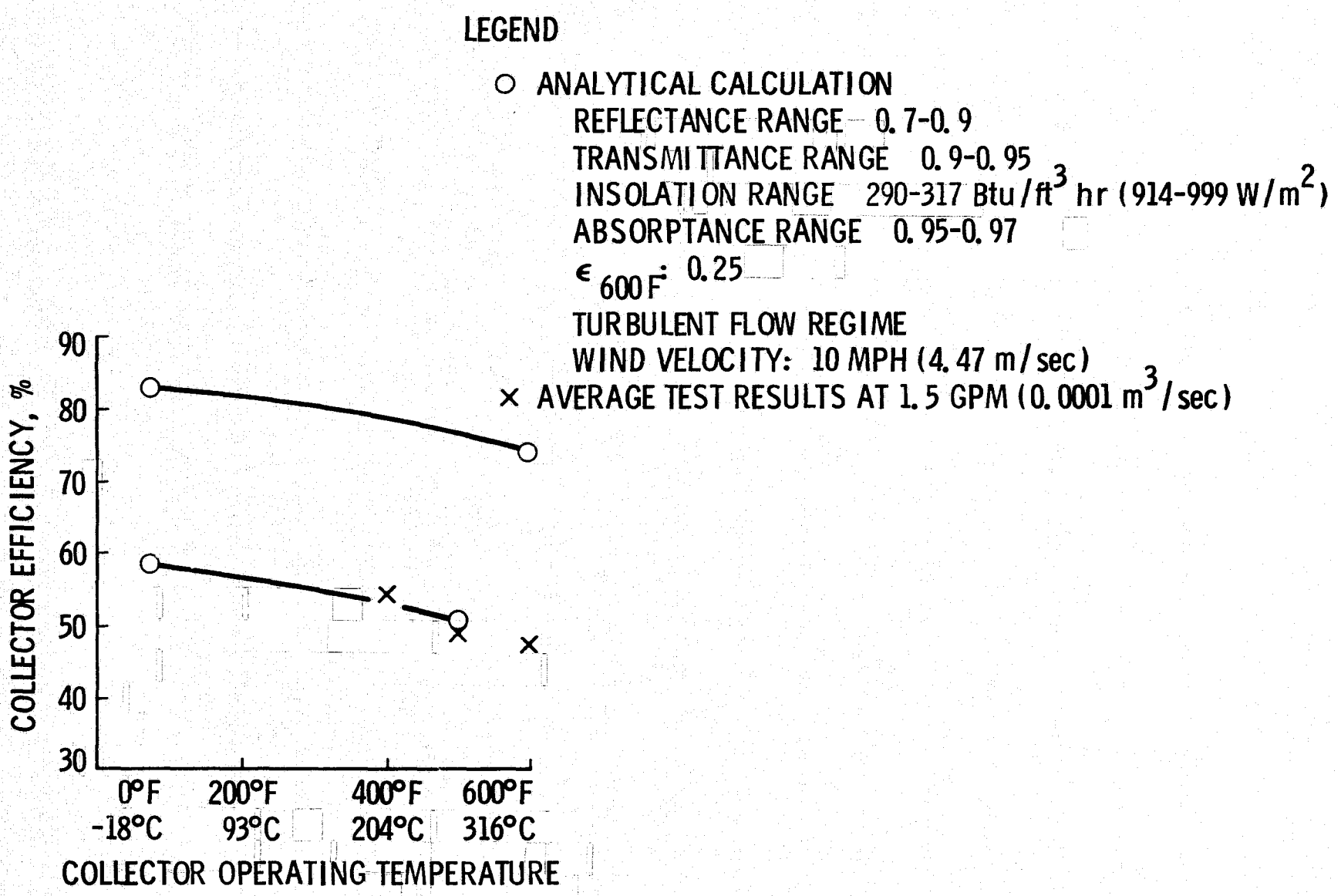

Figure H-1. Probable Efficiency of Parabolic Trough Solar Collectors (Ref. H-1)

	ITEM	REALISTIC EST. FUTURE COST PER FT^2 APERTURE	OPTIMISTIC EST. FUTURE COST PER FT^2 APERTURE
1.	Foundations	$1.00	$1.00
2.	Support Structure and Drive System	3.25	2.50
3.	Tracking System	1.60	1.25
4.	Trough Structure	4.20	2.50
5.	Reflectors	1.25	1.00
6.	Receiver Tubes	2.90	1.25
7.	Fluid System	3.50	3.00
8.	Final Installation	1.00	1.00
		$18.70	$13.50

Figure H-2. Collector Field Costs After Leonard (Ref. H-2)

Comparing to Plant 1:

$$\text{Plant 1} \qquad \frac{\$3.82 \times 10^6}{8.5 \times 10^6} = 0.45 \ \$/\text{BTU}\cdot\text{Hr}$$

$$\text{Plant 2:} \qquad \frac{\$2.10 \times 10^6}{5.0 \times 10^6} = 0.42 \ \$/\text{BTU}\cdot\text{Hr}$$

This is not a significant difference so only Plant 1 will be analyzed further.

If we assume money is worth 10% (plus inflation allowance) to a company, the annual cost of the solar collector investment for Plant 1 is

$$\$3.81 \times 10^6 \times 0.131 \simeq \$500{,}000$$

If we assume operations and maintenance costs are the same as current practice, this amount represents the "fuel cost".

The fraction of the land use by this type collector is about 0.6 to prevent blocking and shading; therefore, the amount of land per well would be:

$$\frac{150{,}000 \text{ ft}^2}{0.6} = 250{,}000 \text{ ft}^2 = 5.7 \text{ acres}$$

Currently, fuel gas, if available, is worth about \$1.50 per 10^6 BTU and crude oil, at \$12/bbl, about \$2 per 10^6 BTU. If oil is used, the fuel cost would be

$$\$2/10^6 \text{ BTU} \times 8.5 \times 10^6 \text{ BTU/hr} \times 24 \text{ hr/day} \times 365 \text{ days/yr}$$
$$\simeq \$150{,}000.$$

The investment for fuel fired equipment is only \$40,000 - \$50,000, so the annual cost of this investment may be neglected.

Some conclusions we can reach from these numbers are as follows:

1. Even using very optimistic assumptions for the solar plant, e.g. no line losses, low operating and maintenance costs, low storage costs, no land use charges, low finance rate, the 3.3 to 1 cost increase over current fuel costs makes a full replacement plant economically unattractive. Even fuel escalations over the foreseeable future (20 years) would probably not change this picture.

2. Using the plant only during the day saves the storage costs of about \$150,000 per year but now saves only half the fuel costs or about \$75,000 per year, so the cost penalty is somewhat less than for the full replacement plant.

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One other possibility was examined, using solar collectors as feed water heaters for the steam generator. For steam at about 600°F and 1500 psia, the distribution of energy is:

water heating = 611.6 - 38 - 573.6 BTU/lb

boiling = 1167.9 - 611.6 = 556.3 BTU/lb

For this approximately 50-50 split, half the fossil fuel could be displaced by a plant with storage and about one-fourth without storage. If we ratio the costs already calculated:

With storage - fossil .5 × 1 = .5
solar .5 × 3.3 = 1.65

Cost 2.15 times current

Without storage - fossil .75 X 1 = .75
solar .25 X 3.3 = .82

Cost 1.57 times current

Neither of these seems attractive for a reasonable time period.

A look was taken at the possibility of using less expensive non-tracking flat plate collectors for part of the feed water heating. If we use them to 150°F., they are about 50% efficient, do not collect as many BTU's due to cosine losses but cost about half as much as the tracking collectors. Thus, they would compare:

tracking: $\frac{A \times 18}{.6 \times 1.4} = 21.43A$

non-tracking: $\frac{A \times 9}{.5 \times 1.0} = 18.00A$

$100 \times \frac{21.43\ A - 18.00A}{21.43\ A} = 16\%$

The amount of load replaced would be:

120 BTU/lb - 38 = 82

611.6 - 120 = 491.6

573.6

$100 \times \frac{491.6}{573.6} = 86\%$ tracking

Cost would be for the full replacement plant:

Fossil	.5 × 1	=	0.5
Tracking Collector	.5 × .86 × 3.3	=	1.42
Flat Plate Collector	.5 × .14 × 3.3 × .84	=	0.19
			2.11

This is not a great improvement over all tracking. In addition, flat plate collectors can only accept (100 x .5 x .14 =) 7% of the load.

If only the flat plate collectors were used, to provide 7% of the total heat, then the cost is:

Fossil	0.93 × 1	=	0.93
Flat plate collector		=	0.19
			1.12

Even this does not pay; the cost penalty is small just because very little of the fuel oil is replaced.

Another possible approach is a solvent injection system with solvent recovery provided by solar energy. This has not been examined.

References

H-1. Treadwell, George W., "Design Considerations for Parabolic Cylindrical Solar Collectors," Sandia Laboratories, SAND 76-0082, Albuquerque, N.M., July 1976

H-2. Leonard, J. A., "Solar Total Energy System Test Facility Including Operating Experience with Parabolic Cylindrical Collector Field," Total Energy Systems Semiannual Review, Sandia Laboratories, Albuquerque, New Mexico, July 1976.

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